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RELATIVE WATER REQUIREMENT OF CORN AND THE SORGHUMS

By EDWIN C. MILLER
Assistant Plant Physiologist, Department of Botany, Kansas Agricultural Experiment Station

INTRODUCTION

During the summers of 1914 and 1915 a physiological study of the water relations of corn and the nonsaccharin sorghums was made at the State Branch Experiment Station at Garden City, Kans. In connection with other experiments it was thought advisable to determine the water requirement of several varieties of these plants. The term "water requirement," as used in this paper, means the ratio of the weight of the water absorbed by the plant to the weight of the dry matter produced.

EXPERIMENTAL METHODS

CLIMATIC DATA

The instruments for recording the climatic conditions consisted of a hydrograph, a thermograph, maximum and minimum thermometers placed in a standard shelter 4 feet from the ground, a rain gauge, an evaporation tank, and an anemometer which measured the wind velocity at a height of 2 feet.

A portion of the weather records for the two seasons averaged for five-day periods is shown in Table I. These show that the climatic conditions for the two seasons were in marked contrast. The summer of 1915 was much cooler than that of 1914 and the rainfall for the months of May, June, July, August, and September in 1915 was approximately three times that for the same months in 1914. The evaporation during 5-day periods is shown graphically in figure 1.

The evaporation for each of the growing months with but one exception was much higher in 1914 than in 1915.

CULTURAL METHODS

The plants were grown in large metal cans made from 22-gauge galvanized iron. These cans were 24 inches in height with a diameter of 15 inches, and under the conditions of these experiments contained about

110 kgm. of soil. Forty of these cans were used in 1914 and 60 in 1915. The upper foot of field soil was worked through a sieve with a ¼-inch mesh and then thoroughly tamped in the cans. The soil was in good tilth, and for both seasons the moisture content ranged from 20 to 21 per cent (dry basis). It had a moisture equivalent of 24 and a wilting coefficient of 13, as calculated by the formula of Briggs and Shantz.[1]

The cans were provided with metal lids which were sealed with ordinary binding tape (Pl. LXXII, fig. 4). This was made waterproof by

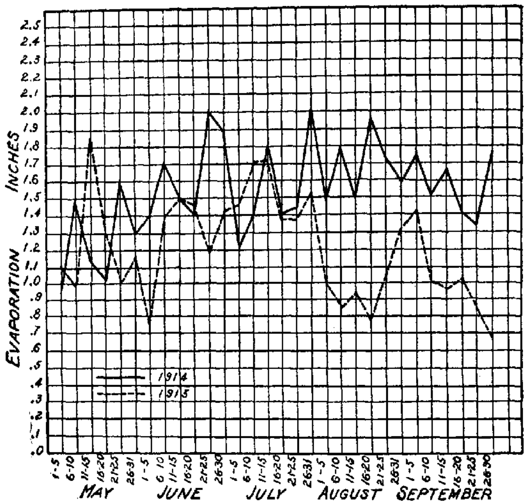


FIG. 1.—Curves of the evaporation at Garden City, Kans., for the growing period of 1915.

giving it a heavy coat of varnish after it was in position. Three 2-inch holes equidistant from one another were made near the periphery of each lid to accomodate the plants. The seeds were planted in the cans and the young plants gradually thinned to the desired number. Three corn plants were grown in each can, both in 1914 and 1915. Six sorghum plants were grown in each can in 1914, but in 1915 the number was reduced to three plants to each can. In order that the plants might be as nearly as possible under the same climatic conditions during the growing season, the seeds of all the plants used were sowed on the same date. These were planted on May 26 in 1914, and on May 22 in 1915.

[1] Briggs, L. J., and Shantz, H. L. The wilting coefficient for different plants and its indirect determination. U. S. Dept. Agr. Bur. Plant Indus. Bul. 230, 83 p., 9 fig., 2 pl. 1912.

TABLE I.—*Summary of the climatic conditions at Garden City, Kans., for 1914 and 1915*

Period (inclusive).	Air temperature (°F.). Average of— Means.	Maximums.	Minimums.	Maximum.	Minimum.	Precipitation.	Evaporation.	Wind velocity per hour.
1914.								
May:						*Inches.*	*Inches.*	*Miles.*
1 to 5	58	68	47	78	44	1.40	0.953	9.0
6 to 10	65	78	51	92	41	.19	1.484	11.8
11 to 15	53	61	44	72	38	.20	1.135	10.9
16 to 20	62	68	55	79	50	.72	.596	13.6
21 to 25	72	84	59	90	57	.12	1.584	10.2
25 to 31	69	79	57	89	49	1.00	1.294	6.9
June:								
1 to 5	76	87	65	92	62	.19	1.432	13.0
6 to 10	77	89	64	91	51	.21	1.728	15.2
11 to 15	76	88	63	96	59	.61	1.520	9.3
16 to 20	76	89	62	99	58	.39	1.409	6.4
21 to 25	82	94	69	98	64	....	1.991	9.9
26 to 30	77	94	59	103	51	.04	1.862	7.7
July:								
1 to 5	74	85	62	94	53	.15	1.200	6.1
6 to 10	77	91	60	93	53	.10	1.440	4.7
11 to 15	86	99	69	103	64	....	1.822	5.7
16 to 20	76	87	62	101	58	.21	1.416	7.7
21 to 25	81	94	65	98	64	.10	1.451	5.7
26 to 31	83	98	66	102	64	Trace.	2.074	5.7
August:								
1 to 5	77	93	65	95	61	.38	1.477	6.1
6 to 10	77	91	62	95	56	Trace.	1.792	8.0
11 to 15	77	91	62	95	58	.19	1.474	7.0
16 to 20	82	99	64	102	62	.06	1.959	8.2
21 to 25	77	91	61	99	50	.01	1.745	7.5
25 to 31	73	87	60	94	54	Trace.	1.563	7.4
September:								
1 to 5	77	94	60	103	55	....	1.739	7.5
6 to 10	79	96	64	102	59	.01	1.501	8.6
11 to 15	75	89	58	96	48	.03	1.653	11.4
16 to 20	77	90	60	97	56	....	1.390	7.6
21 to 25	63	80	44	85	37	.11	1.343	6.4
26 to 30	67	86	51	90	47	....	1.740	11.1
1915.								
May:								
1 to 5	53	65	38	76	31	.79	1.187	10.0
6 to 10	56	69	44	81	32	....	.985	7.7
11 to 15	71	87	55	94	46	....	1.857	10.8
16 to 20	46	55	39	68	32	2.38	1.324	12.2
20 to 25	67	78	57	90	44	.07	1.069	8.6
25 to 31	55	65	47	72	39	1.15	1.169	8.1
June:								
1 to 5	65	75	58	81	55	.64	.738	8.7
6 to 10	64	78	52	86	36	.94	1.386	8.6
11 to 15	66	78	53	87	50	....	1.490	8.0
16 to 20	71	85	61	95	56	.07	1.485	8.8
21 to 25	69	79	58	91	56	.62	1.181	8.5
26 to 30	72	84	59	88	57	.69	1.419	7.1
July:								
1 to 5	66	77	55	83	49	.57	1.451	8.8
6 to 10	76	90	60	96	54	.51	1.732	8.6

TABLE I.—*Summary of the climatic conditions at Garden City, Kans., for 1914 and 1915*—Continued

Period (inclusive).	Air temperature (°F).					Precipitation.	Evaporation.	Wind velocity per hour.
	Average of—			Maximum.	Minimum.			
	Means.	Maximums.	Minimums.					
1915.								
July—Continued.						*Inches.*	*Inches.*	*Miles.*
11 to 15	81	97	67	101	64	0.06	1.743	6.7
16 to 20	72	84	62	96	56	.15	1.407	7.0
21 to 25	74	85	61	91	56	.13	1.397	5.5
25 to 31	75	74	64	90	62	.24	1.528	6.8
August:								
1 to 5	69	83	56	90	51	.90	1.012	5.8
6 to 10	70	80	60	94	56	5.11	.860	4.9
11 to 15	72	83	61	86	59	.10	.927	2.7
16 to 20	61	80	61	84	57	.03	.790	3.2
21 to 25	70	81	60	84	57	.46	1.018	4.4
25 to 31	63	77	50	85	40	....	1.313	4.7
September:								
1 to 5	68	83	55	87	51	.82	1.424	7.4
6 to 10	69	81	56	91	54	....	1.029	6.3
11 to 15	71	84	60	97	53	Trace.	.983	7.2
16 to 20	69	82	55	87	39	.20	1.072	5.2
21 to 25	66	76	58	84	50	1.00	.864	18.2
25 to 30	56	67	48	78	44	.25	.665	4.4

The holes in the lids were made water-tight by using a mixture of approximately 16 parts by weight of beeswax to 1 part of Venetian turpentine. Under ordinary conditions the young seedlings of the corn and sorghum can readily penetrate this wax. After the plants had emerged through the wax, it was replaced by a mixture containing a much smaller amount of Venetian turpentine, in order to secure a seal that would remain firm around the plants during the hot summer weather. The lids of the cans were given a heavy coat of white paint and were then covered with a layer of burlap in order to protect them from excessive heat. The water lost by the plants was replaced every 48 hours by the method used by Briggs and Shantz [1] in their extensive work on the water requirement of plants.

It was thought advisable to determine the water requirement based on the dry weight of both the aerial portions and the roots of the plants. The water requirement was obtained in this manner for Pride of Saline corn, Blackhull kafir, Dwarf milo, and Dwarf Blackhull kafir. The method used in the isolation of the root systems of these plants has been previously reported by the writer int his Journal.[2]

[1] Briggs, L. J., and Shantz, H. L. The water requirement of plants. I. Investigations in the Great Plains in 1910 and 1911. U.S. Dept. Agr. Bur. Plant Indus. Bul. 284, 49 p., 2 fig., 11 pl. 1913.

——— ——— The water requirement of plants. II. A review of the literature. U.S. Dept. Agr. Bur. Plant Indus. Bul. 285, 96 p., 5 fig. 1913.

——— ——— The relative water requirement of plants. *In* Jour. Agr. Research, v. 3, no. 1, p. 1-64, 1 fig., pl. 1-7. 1914.

[2] Miller, E. C. A comparative study of the root systems and leaf areas of corn and the sorghums. *In* Jour. Agr. Research, v. 6, no. 9, p. 311-332. 1916.

SCREENED INCLOSURE

The plants were grown in a screened shelter in order to protect them from the hailstorms and severe winds that are frequent in this region. The inclosure was 20 feet square and had a flat top 10 feet from the ground. It consisted of a framework of 2 by 4 inch studding spaced 3 feet apart and covered on both the top and sides by a wire netting with a ¼-inch mesh. Cheesecloth was placed around the sides of the inclosure to a height of 4½ feet from the ground. This was held in position by poultry netting tacked over the outside (Pl. LXX, fig. 1).

The bottom of the inclosure was provided with a smooth, rigid floor made of matched pine lumber. The cans were placed in three double rows running north and south inside the inclosure, with a space of 2 feet between each row. The height of the floor was such that the upper surface of the cans came to within 1½ feet of the top of the cheesecloth.

The rate of evaporation inside and outside the shelter was determined by two Livingston[1] porous-cup atmometers. These were renewed every three or four weeks. They were connected with burettes which were graduated to 0.1 c. c., and readings were made twice each day. The atmometer outside the inclosure was placed at a distance of 2 feet from the ground in the center of a plot that was planted to corn. The atmometer in the inclosure was placed a few inches above the upper surface of the cans during the early part of the growing season and 2 feet above their tops when the plants had reached 3 feet in height. The monthly evaporation for the two seasons from the porous-cup atmometers, having a coefficient of 0.74 is given in Table II.

TABLE II.—*Monthly evaporation (in cubic centimeters) inside and outside the screened inclosure for 1914 and 1915*

Period.	Outside.	Inside.	Ratio.
1914.			
June 10 to July 10	2,595	1,494	1.7
July 10 to Aug. 10	2,317	1,593	1.4
Aug. 10 to Sept. 10	2,124	1,462	1.4
1915.			
June 10 to July 10	2,028	1,274	1.5
July 10 to Aug. 10	1,627	1,233	1.3
Aug. 10 to Sept. 10	1,589	976	1.6

The rate of evaporation within the inclosure as measured by the porous-cup atmometers, was only approximately two-thirds as high as that in the field. Briggs and Shantz[2] found that plants grown in such a shelter had a water requirement approximately 20 per cent lower than

[1] Livingston, B. E. The Relation of Desert Plants to Soil Moisture and to Evaporation. 78 p., illus., Washington, D. C., 1906. (Carnegie Inst. Washington, Pub. 50.) Literature cited, p. 77–78.

—— Operation of the porous-cup atmometer. *In* Plant World, v. 13, no. 5, p. 111–119. 1910.

[2] Briggs, L. J., and Shantz, H. L., 1913. Op. cit.

plants of the same kind grown in the open. The relative water requirment, however, is probably affected little, if at all, by the shading due to an inclosure of this kind, and it offers the only scientific method for studying the relative transpiration of plants under the severe climatic conditions experienced in this region.

WEIGHING THE CANS

Each can was placed on a small wooden platform, which was provided with a screw eye at either end and mounted on four iron castors. By means of an iron rod, hooked at one end and bent into a handhold at the other, the cans could be moved easily wherever desired (Pl. LXX, fig. 2). The cans were pulled over a track made of pine flooring to a small scale house located 12 feet from the shelter and were weighed every 48 hours on platform scales that were sensitive to 50 gm. (Pl. LXX, fig. 1). In this manner two men could easily weigh the 60 cans in less than 1½ hours.

EXPERIMENTAL DATA

CORN

Four varieties of corn were grown in 1914 and three varieties in 1915. The results for the two years are shown in Tables III and IV.

TABLE III.—*Water requirement of Pride of Saline corn at Garden City, Kans., in 1914 and 1915*

Period of growth.	Pot No.	Number of plants.	Dry matter, including roots.	Dry matter, without root (stem and leaves).	Water transpired.	Water requirement based on— Total dry weight, including roots.	Total dry weight, excluding roots (stem and leaves).
1914.			*Gm.*	*Gm.*	*Kgm.*		
May 26 to Aug. 22.	13	3	164.3	150.6	53.5	325.8	355.4
	14	3	169.8	153.9	63.3	373.1	411.7
	15	3	147.0	131.4	61.7	420.0	469.9
	16	3	180.1	163.7	61.4	341.0	375.3
Mean	.....	.....	.....	.....	.....	365±15	403±18
1915.							
May 22 to Aug. 25.	17	3	236.1	205.6	56.9	241.1	276.0
	18	3	285.6	252.5	64.2	225.1	254.6
	19	3	260.4	234.4	63.4	243.7	270.7
	20	3	230.6	202.4	55.3	240.0	273.4
	21	3	244.3	211.2	58.1	238.1	275.5
	22	3	260.0	228.3	59.2	227.9	259.6
	23	3	.....	165.4	46.6	.....	282.2
	24	3	.....	178.6	46.0	.....	257.9
	25	3	.....	180.5	46.7	.....	259.0
	26	3	.....	154.4	40.6	.....	263.0
Mean	.....	.....	.....	.....	.....	236±3	267±2

TABLE IV.—*Water requirement of Sherrods White Dent, Chinese, and hybrid corn at Garden City, Kans., in 1914 and 1915*

Variety and period of growth.	Pot No.	Number of plants.	Dry matter, excluding roots (stem and leaves).	Water transpired.	Water requirement.
1914.			*Gm.*	*Kgm.*	
Sherrods White Dent, May 26 to Aug. 22	17	3	133.3	54.7	410.8
	18	3	142.4	50.7	356.3
	19	3	143.7	60.8	423.3
Mean					396±16
Chinese, May 26 to Aug. 22	20	3	136.1	58.1	427.1
	21	3	157.3	64.5	410.3
Mean					418±7
Hybrid F_3 H_{58},[a] May 26 to Aug. 22	22	3	120.1	40.2	335.3
	23	3	143.3	50.5	361.8
	24	3	142.6	54.4	381.4
	25	3	155.0	51.9	342.0
Mean					355±8
1915.					
Sherrods White Dent, May 22 to Aug. 18	27	3	145.7	42.8	293.7
	28	3	150.4	43.7	291.0
	29	3	145.2	41.0	282.9
	30	3	120.5	39.8	330.9
Mean					299±8
Hybrid F_4 H_{58},[a] May 22 to Aug. 25	43	3	239.7	54.1	225.9
	44	3	125.6	33.3	265.7
	45	3	137.7	36.3	264.0
	46	3	248.5	58.0	233.4
	47	3	249.3	60.7	243.7
Mean					246±6

[a] This hybrid has the following origin: The female parent was a plant belonging to the F_1 generation of a cross between Sherrods White Dent corn ♀ and white Chinese corn ♂. The male parent was a plant of the variety known as Esperanza (Mexican corn). The cross was made on the breeding grounds of the Department of Botany of the Kansas Experiment Station in 1910.

Four cans of Pride of Saline corn were grown in 1914 and ten in 1915. These plants varied in mature height from 5 to 6 feet, but produced no ears during either season. The plants grew from May 26 to August 22 in 1914, and from May 22 to August 25 in 1915. The water requirement of Pride of Saline corn, based on the total dry matter, including the roots, was found to be 365±15 in 1914 and 236±3 in 1915. The water requirement, based on the total dry matter of the aerial parts of the plants, was 403±18 and 267±2 for the years 1914 and 1915, respectively (Pl. LXXII, fig. 2).

Sherrods White Dent corn was grown in three cans in 1914 and in four cans in 1915. In 1914 the seeds were planted on May 26 and the

plants were harvested on August 22, while in 1915 they were planted on May 22 and harvested on August 18. The water requirement of this variety of corn, based on the total dry matter of the aerial parts, was found to be 396±16 in 1914 and 299±8 in 1915.

In 1914 two cans were planted to white Chinese corn. The growing season of these plants was from May 26 to August 22. The water requirement, based on the dry weight of the aerial parts, was 418±7.

In 1914 four cans were planted to the F_3 generation of a segregate of a hybrid corn developed by the Department of Botany of the Kansas Experiment Station. Five cans of the F_4 generation of this hybrid were grown in 1915. Its water requirement, based on the total dry matter of the aerial parts, was 355±8 and 246±6, for the years 1914 and 1915, respectively.

SORGHUMS

Dwarf milo and Blackhull kafir were the only sorghums grown in 1914. In addition to these two varieties, dwarf black-hulled white kafir, feterita, and sudan grass were grown in 1915. The results for the two seasons are shown in Tables V and VI.

Six cans of Dwarf milo were planted in 1914 and eight cans in 1915. The plants in the former year reached a height of 3 feet, and during the latter year they stood 4½ feet high (Pl. LXXI, fig. 1). The growing season was from May 26 to August 22 in 1914, and from May 22 to September 3 in 1915. The water requirement, based on the total dry matter, including the roots, was found to be 319±5 in the former year and 228±3 in the latter. The water requirement, based on the total dry matter of the aerial parts, was 340±5 and 244±3 for the years 1914 and 1915, respectively. The water requirement, based on the production of grain, was 1,022±100 in 1914 and 508±6 in 1915.

Blackhull kafir was grown in six cans in 1914 and in eight cans in 1915. The seed was planted on May 26 and the plants were harvested on September 3 in 1914, while in 1915 the growing period was from May 22 to September 18. The plants reached a height of 6 feet in each of the growing seasons (Pl. LXXII, fig. 3). The water requirement, based on the total dry matter, including the roots, was 305±6 in 1914 and 204±2 in 1915, while the water requirement, based on the total dry weight of the aerial parts, was 325±7 for the former year and 217±2 for the latter. The water requirement, based on the production of grain, was 1,178±45 in 1914 and 696±19 in 1915.

TABLE V.—*Water requirement of Dwarf milo and Blackhull kafir at Garden City, Kans., in 1914 and 1915*

DWARF MILO

Period of growth.	Pot No.	Number of plants.	Dry matter, including roots.	Dry matter, without roots.	Grain.	Stem and leaves.	Water transpired.	Water requirement based on— Total dry weight, including roots.	Total dry weight, excluding roots.	Grain.	Stem and leaves.
			Gm.	*Gm.*	*Gm.*	*Gm.*	*Kgm.*				
1914.											
May 26 to August 22..	1	6	199.0	187.3	71.8	115.5	61.4	308.9	328.2	855.3	532.2
	2	6	172.2	161.5	40.4	121.1	55.8	324.2	345.6	1,381.9	461.0
	3	6	186.8	173.7	45.0	128.9	65.1	348.7	374.6	1,447.7	505.4
	4	6	196.4	184.4	79.3	105.1	60.6	308.7	328.7	764.4	576.8
	5	6	173.7	161.7	58.8	102.9	51.6	297.5	319.9	879.0	502.3
	6	6	169.2	159.7	68.5	91.2	55.1	326.0	345.3	805.2	604.8
Mean..	....	....	....	....	....	....	....	319 ± 5	340 ± 5	1022 ± 100	530 ± 15
1915.											
May 22 to September 3...	1	3	228.1	214.6	103.1	111.5	51.5	225.7	239.9	499.5	461.8
	2	3	239.1	226.4	114.6	111.8	50.5	211.5	223.3	437.2	452.3
	3	3	245.4	231.4	105.6	125.8	55.3	225.7	239.3	524.5	440.3
	4	3	245.9	223.3	102.0	121.3	56.1	228.2	251.3	549.1	462.6
	5	3	248.3	233.3	109.6	123.7	55.6	224.1	238.5	507.7	449.8
	6	3	231.6	217.6	107.6	110.0	54.7	236.3	251.5	508.7	497.6
	7	3	247.3	230.5	114.7	115.8	60.4	244.4	262.2	526.7	521.8
	8	3	240.8	225.8	108.3	117.5	55.3	229.8	245.1	511.0	471.0
Mean..	....	....	....	....	....	....	....	228 ± 3	244 ± 3	508 ± 6	469 ± 7

BLACKHULL KAFIR

Period of growth.	Pot No.	Number of plants.	Dry matter, including roots.	Dry matter, without roots.	Grain.	Stem and leaves.	Water transpired.	Water requirement based on— Total dry weight, including roots.	Total dry weight, excluding roots.	Grain.	Stem and leaves.
1914.											
May 26 to September 3...	7	4	234.4	217.9	54.5	163.4	75.0	320.0	344.2	1,376.4	459.1
	8	5	247.0	234.1	66.7	167.4	68.1	276.0	291.2	1,022.1	407.3
	9	5	226.8	212.6	55.5	157.1	67.7	298.7	318.7	1,220.9	431.3
	10	6	233.3	219.5	60.5	159.0	78.1	335.0	356.0	1,291.9	491.5
	11	4	186.5	175.6	52.0	123.6	58.6	314.5	334.1	1,126.7	474.6
	12	6	278.1	257.3	77.3	180.0	79.8	287.0	310.0	1,032.4	443.2
Mean..	....	....	....	....	....	....	....	305 ± 6	325 ± 7	$1,178\pm45$	451 ± 7
1915.											
May 22 to September 18..	9	3	360.7	341.7	126.7	215.0	74.8	207.5	219.1	590.9	348.2
	10	2	233.9	219.3	72.1	147.2	49.2	210.7	224.7	683.6	334.8
	11	3	324.7	299.7	92.4	207.3	67.8	208.9	226.3	734.3	327.3
	12	3	311.3	287.8	81.2	206.6	64.5	207.3	224.2	794.8	312.3
	13	3	325.0	310.3	97.2	213.1	67.9	208.9	218.8	698.5	318.6
	14	3	363.8	342.8	89.6	253.2	70.9	194.9	206.8	791.5	280.0
	15	3	353.9	333.8	114.3	219.5	70.6	199.5	211.5	617.7	307.6
	16	3	368.9	354.2	109.6	244.6	72.0	195.2	203.3	657.3	294.5
Mean..	....	....	....	....	....	....	....	204 ± 2	217 ± 2	696 ± 19	315 ± 5

TABLE VI.—*Water requirement of Dwarf Blackhull kafir, feterita, and Sudan grass at Garden City, Kans., in 1915*

Plant and period of growth.	Pot No.	Number of plants.	Dry matter, including roots.	Dry matter, without roots.	Grain.	Stem and leaves.	Water transpired.	Water requirement based on— Total dry weight, including roots.	Total dry weight, excluding roots.	Grain.	Stem and leaves.
1915.			*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Kgm.*				
Kafir, Dwarf Blackhull, May 22 to September 11	31	3	265.7	249.7	107.0	142.7	56.4	212.3	225.9	527.3	395.4
	32	3	235.4	221.8	88.4	133.4	48.3	205.3	217.9	546.8	362.3
	33	3	273.2	257.8	119.9	137.9	56.7	207.3	220.2	473.4	411.6
	34	2	179.2	168.8	71.7	97.1	37.5	209.7	222.6	524.1	387.0
	35	3	247.1	230.2	95.1	135.1	50.0	202.3	217.2	525.8	370.1
Mean								207±2	221±2	519±8	385±6
Feterita, May 22 to September 6	36	3	......	175.6	59.6	116.0	42.6	......	242.7	715.2	367.5
	37	3	......	204.7	66.0	138.7	49.4	......	242.1	748.4	365.1
	38	3	......	158.8	55.7	103.1	41.8	......	263.3	750.8	405.6
	39	2	......	143.1	42.0	101.1	35.5	......	248.2	845.7	351.3
	40	3	......	182.6	52.4	130.2	45.3	......	248.3	865.2	348.2
Mean								......	249±2	785±24	367±6
Sudan grass, May 22 to September 14	41	5	......	186.4	33.2	153.2	52.5	......	281.6	1,581.3	342.6
	42	5	......	173.6	28.4	145.2	50.7	......	292.5	1,788.3	349.7
	43	5	......	176.4	42.5	133.9	60.5	......	343.3	1,425.2	452.3
Mean								......	306±15	1,598±76	381±28

Dwarf Blackhull kafir was grown only in 1915. The growing season for these plants was from May 22 to September 11. The water requirement, based on the total dry matter, including the roots, was 207±2, and based on the total dry weight of the aerial portions, was 221±2. The water requirement, based on the production of grain, was 519±8 (Pl. LXXI, fig. 2).

Feterita was grown in five cans in 1915. The seed was planted on May 22 and the plants were harvested on September 6. The water requirement, based on the total dry matter of the aerial parts, was 249±2, while the water requirement, based on the seed production was 785±24 (Pl. LXXI, fig. 3).

Three cans were planted to Sudan grass in 1915. These plants reached a height of 6 feet during the growing period from May 22 to September 14 (Pl. LXXII, fig. 1). The water requirement, based on the dry weight of the aerial parts, was 306±15 and, based on the production of grain, was 1598±76.

SUMMARY

The water requirement was determined for four varieties of corn and two varieties of sorghum in 1914 and for three varieties of corn and five varieties of sorghum in 1915.

The plants were grown in large sealed galvanized-iron cans which contained approximately 110 kgm. of soil. The soil had a wilting coefficient of 13, and under the conditions of the experiment it had a moisture content of 20 to 21 per cent (dry basis). This moisture content was kept approximately constant by replacing every 48 hours the water that had been lost by transpiration.

Three plants of corn were grown in each can during both seasons. Six sorghum plants were grown to each can in 1914, but in 1915 the number of plants was reduced to three plants to a can.

The plants were grown in a screened inclosure in order to protect them from the hailstorms and severe winds that are prevalent in western Kansas. The rate of evaporation in such a shelter was found to be only two-thirds as high as under field conditions.

The season of 1915 was cooler and more humid, and the rate of evaporation much lower than in 1914. As a consequence the water requirement of the former year was only about 66 per cent of that of the latter year. A summary of the water requirement for the two seasons is given in Table VII.

TABLE VII.—*Summary of the water requirement of the varieties of corn and sorghum grown at Garden City, Kans., in 1914 and 1915*

Plant and period of growth.	Water requirement based on—			
	Dry matter, including roots.	Dry matter, excluding roots.	Grain.	Stem and leaves.
1914.				
CORN:				
Pride of Saline, May 26 to August 22	365±15	403±18	....	403±18
Sherrods White Dent, May 26 to August 22	....	396±16	....	396±16
Hybrid F_3 H_{58}, May 26 to August 22	....	355± 8	....	355± 8
Chinese, May 26 to August 22	....	418± 7	....	418± 7
KAFIR:				
Blackhull, May 26 to September 3	305± 6	325± 7	1,178± 45	451± 7
MILO:				
Dwarf, May 26 to August 22	319± 5	340± 5	1,022±100	530±15
1915.				
CORN:				
Pride of Saline, May 22 to August 25	236± 3	267± 2	....	267± 2
Sherrods White Dent, May 22 to August 18	....	299± 8	....	299± 8
Hybrid F_4 H_{58}, May 22 to August 25	....	246± 6	....	246± 6

TABLE VII.—*Summary of the water requirement of the varieties of corn and sorghum grown at Garden City, Kans., in 1914 and 1915*—Continued

Plant and period of growth.	Water requirement based on—			
	Dry matter, including roots.	Dry matter, excluding roots.	Grain.	Stem and leaves.
1915.				
KAFIR:				
Blackhull, May 22 to September 18.	204± 2	217± 2	696± 19	315± 5
Dwarf Blackhull, May 22 to September 11	207± 2	221± 2	519± 8	385± 6
MILO:				
Dwarf, May 22 to September 3	228± 3	244± 3	508± 6	469± 7
FETERITA:				
May 22 to September 6	....	249± 2	785± 24	367± 6
SUDAN GRASS: May 22 to September 14.	....	306±15	1,598± 76	381±28

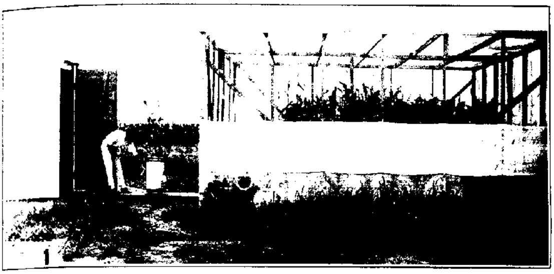
Using the water requirement of Blackhull kafir as 1, the water requirement of the plants grown in 1914 would be as follows: Dwarf milo 1.04, hybrid corn 1.09, Sherrods White Dent corn 1.22, and Pride of Saline corn 1.24. In 1915, if the water requirement of Blackhull kafir be considered as 1, the water requirement of Dwarf Blackhull kafir would be 1.02; Dwarf milo, 1.12; feterita, 1.14; hybrid corn, 1.17; Pride of Saline corn, 1.23; Sherrods White Dent corn, 1.37; and Sudan grass, 1.41.

PLATE LXX

Fig. 1.—General view of the screened inclosure and the scale house.

Fig. 2.—Method of moving the cans.

Fig. 3.—General view of the plant shelter and the surrounding country at Garden City, Kans.



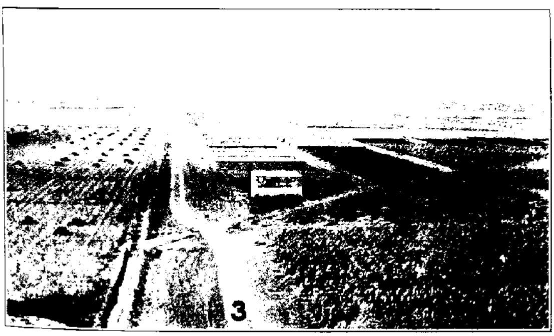


PLATE LXXI

Fig. 1.—Dwarf milo, grown May 22 to September 3, 1915. Water requirement based on total dry matter, including roots, 228±3. Based on dry matter, excluding roots, 244±3. Average of 8 cans.

Fig. 2.—Dwarf Blackhull kafir, grown May 22 to September 11, 1915. Water requirement based on total dry matter, including roots, 207±2. Based on total dry matter, excluding roots, 221±2. Average of 5 cans.

Fig. 3.—Feterita, grown May 22 to September 6, 1915. Water requirement based on total dry matter, excluding roots, 249±2. Average of 5 cans.

PLATE LXXII

Fig. 1.—Sudan grass, grown May 22 to September 14, 1915. Water requirement based on total dry matter, excluding roots, 306 ± 15. Average of 3 cans.

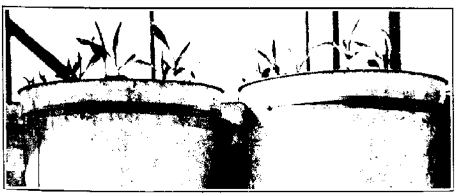
Fig. 2.—Pride of Saline corn, grown May 22 to August 25, 1915. Water requirement based on total dry matter, including roots, 236 ± 3. Based on total dry matter, excluding roots, 267 ± 2. Average of 10 cans.

Fig. 3.—Blackhull kafir, grown May 22 to September 18, 1915. Water requirement based on total dry matter, including roots, 204 ± 2. Based on total dry matter, excluding roots, 217 ± 2. Average of 8 cans.

Fig. 4.—Method of sealing the lids with tape and the wax seal around the plants.


2


3



AVAILABILITY OF MINERAL PHOSPHATES FOR PLANT NUTRITION [1]

By W. L. BURLISON,

Associate Professor, Crop Production, Agricultural College, and Associate Chief, Crop Production, Illinois Agricultural Experiment Station [2]

INTRODUCTION

Phosphorus is the key to permanent systems of agriculture for a large portion of the common soils of the corn belt. These soils contain, as an average, 5,000 pounds of nitrogen, 1,200 pounds of phosphorus, and 35,000 pounds of potassium for the surface soil to the depth of 6⅔ inches. If the land were producing corn at the rate of 100 bushels per acre, the nitrogen would be sufficient for 50 crops, the phosphorus for 70 crops, and the potassium for about 1,842 crops. The nitrogen supply can be maintained by the growth and judicious management of leguminous crops. Potassium is present in quantities adequate for many years. With phosphorus the problem is different. This element can not be gathered from the soil air by legumes; nor is it one of unlimited supply. When once removed, phosphorus must be returned to the land in crop residues, in farm manures, or in commercial fertilizers which contain phosphorus.

Since the introduction of commercial fertilizers, more or less discussion has been carried on concerning the value of insoluble mineral phosphates as a source of phosphorus for the nutrition of plants. In Europe (28, p. 329)[3] the highest authorities on agricultural problems have discouraged the use of insoluble phosphates, while in America scientists and practical men have disagreed. Investigations which have been conducted on the use of insoluble minerals are by no means conclusive. Therefore it is the purpose of the work reported in the following pages to throw more light on this question, which is of so great economic importance and scientific significance. The subject matter will be presented according to the following divisions:

I. Review of literature regarding the availability of phosphate minerals.

II. The availability of phosphorus in Tennessee brown rock phosphate for wheat (*Triticum vulgare*), oats (*Avena sativa*), rye (*Secale cereale*), barley (*Hordeum sativum hexastichon*), cowpeas (*Vigna catjang*), soybeans (*Glycine hispida*), timothy (*Phleum pratense*), red clover (*Trifolium pratense*), and alfalfa (*Medicago sativa*).

[1] This paper is submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Agronomy in the Graduate School of the University of Illinois, 1915.

[2] The author wishes to express his appreciation for the suggestions and encouragement tendered by Dr. C. G. Hopkins and Dr. A. L. Whiting, of the Illinois Experiment Station.

[3] Reference is made by number to "Literature cited," p. 513-514.

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III. A comparative study of the productive powers of six mineral phosphates for farm crops.

IV. The influence of fermenting dextrose and crop residues on the availability of phosphorus in finely ground rock phosphate.

V. The influence of the size of particles on the availability of phosphorus in mineral phosphates.

REVIEW OF LITERATURE

The availability of mineral phosphates for plant nutrition has been under investigation at various institutions for more than half a century. Among the earlier scientists who attempted to determine the availability of the phosphorus in mineral phosphates was Dyer (4), who found that undissolved phosphate produced better returns than dissolved phosphate for swedes and oats. Frear (5) studied the comparative value of various phosphorus carriers for farm crops. Finely ground bone and reverted phosphate produced the largest number of mature stalks of corn, and finely ground bone, the highest yield of ears. Superphosphate and certain mineral or raw phosphates were put in field trials by Johnson (9), and for corn, dissolved bone black was superior to others tested. Bishop (1) grew soybeans in pot cultures and concluded that concentrated phosphate and acid phosphate were more desirable than Florida soft rock and iron and aluminum phosphate. Equivalent amounts of different carriers of phosphate were employed by Hess (7) in a 4-year rotation of corn, oats, wheat, and grass. Finely ground bone gave the highest yields of wheat, with raw rock second. Ground bone was most effective for corn, while for oats insoluble ground bone seemed to be satisfactory. South Carolina rock was very useful for clover. Jordan (10) conducted two experiments at the Maine Station with different forms of phosphate. In the first experiment the minerals were applied in equal quantities. For the first two years the acid phosphate gave the highest returns, but later bone meal took the lead. Raw rock was only about half as productive as the other two. In the second trial equal money values of phosphates were applied; and the author points out that, with but one exception, the raw rock gave larger returns than acid phosphate. The work of Jordan, previously mentioned, was continued by Merrill (15), who used pure sand cultures in the greenhouse. Two facts are clear from Merrill's work. First, plants differ widely in their power to assimilate phosphorus from different phosphates. Second, turnips and rutabagas gave almost as good results with raw rock phosphate as with acid phosphate. Later, at the New York Station, Jordan (11) continued the work which he had begun at the Maine Station. His results are in accord with the work previously reported by himself and Merrill.

In 1890 Goessman (2) outlined what has since become a most extensive investigation, concerning the availability of phosphate minerals. In reporting on this work Brooks says (3, p. 104) that—

It is possible to produce profitable crops of most kinds by liberal use of natural phosphates, and in a long series of years there might be a considerable money saving in depending, at least in part, upon these rather than upon the higher-priced dissolved phosphates.

Results from a second series of experiments begun in Massachusetts in 1897, along the same line as that outlined by Goessman, indicate that phosphatic slag was "exceedingly available for crops, but the Florida soft phosphate was very inferior. For certain crops, South Carolina rock gave surprisingly good returns * * *."

Prianishnikov (20) states that lupins and peas have a very marked ability to obtain phosphorus from natural phosphate, while wheat and oats must be assisted by the solvent powers of the soil or they can not produce normal crops. Schloessing (22) concludes from his experiments that it is not necessary that phosphate should be in a state of solution, since the roots of plants are able to dissolve the phosphorus compounds without the intervention of water.

Patterson (18) reports results, based on a study of various phosphates, which indicate that reverted phosphate gave the highest average yield for corn, wheat, and hay. South Carolina rock phosphate produced slightly better yields than bone black, and Florida soft rock phosphate was quite available for wheat. Wheeler and Adams (30, 31, 32) found raw phosphate profitable for peas, oats, crimson clover, and Japanese millet when used on unlimed land; but for flat turnips, beets, and cabbage it gave poor yields. They are of the opinion that rock phosphate is likely to be most useful when applied to moist soils rich in organic matter, where legumes, corn, and "possibly wheat and oats are to be grown."

Thorne (24, 25), of Ohio, in 1897 inaugurated a very extensive study of the comparative value of raw rock phosphate and acid phosphate used in conjunction with manure. Where, in computing the yields of corn, wheat, and clover, he took the average of all the unfertilized plots as a basis for comparison, he reports (24, p. 18)—

By this method of calculation the average increase on Plots 2 [floats plus yard manure] and 3 [floats plus stall manure] combined is found to be practically the same as that on Plots 5 [acid phosphate plus yard manure] and 6 [acid phosphate plus stall manure] combined, but when the larger cost of the acid phosphate is deducted the net gain is a little greater on Plots 2 and 3 [with raw phosphate].

By another method of computing the increase he obtains results less favorable to raw phosphate.

Truog (27) has demonstrated rather clearly that farm crops are variable in their ability to secure phosphorus from different sources. Nine of the ten crops tested by him made a better growth on aluminum phos-

phate than on calcium phosphate, and "six made better growth on iron phosphate than on calcium phosphate."

Under the direction of Hopkins (8), the Illinois Experiment Station is conducting probably the most extensive investigation of any in the world on the use of rock phosphate. Some of the most interesting results were obtained from a field near Galesburg, Knox County, Ill., on brown silt loam prairie soil.

> Phosphorus applied in fine-ground natural rock phosphate in part as top dressing, and with no adequate provision for decaying organic matter, paid only 47 per cent on the investment as an average of the first three years. But it should be kept in mind that the word *investment* is here used in its proper sense, for the phosphorus that was removed in the increase produced was less than 2 per cent of the amount applied, and that removed in the total crops less than one-third. During the last six years, however, the phosphorus has paid 130 per cent on the investment, even though two-thirds of the application remains to positively enrich the soil (8, p. 15).

Newman (16) investigated the use of floats with and without cottonseed meal. He found a marked increase in availability where organic matter was used in conjunction with the mineral phosphate. Later experiments by Newman and Clayton (17) confirmed the above results. Lupton (13) continued the work of Newman, but used acid phosphate as a check on the raw rock phosphate, both with and without organic matter. His results are also in accord with Newman's earlier experiments. Where floats were mixed with cottonseed meal and allowed to ferment, the data seemed to show that the fermentation of the material had very little, if any, influence on the availability of the phosphate. Pfeiffer and Thurman (19) found no beneficial results from composting raw rock phosphate with decaying organic matter. In Canada (23) fermenting manures were found to have only slightly solvent action on composted rock phosphate.

Hartwell and Pember (6) mixed fresh cow manure and floats and allowed them to ferment. They feel that there was practically no increase in the availability of phosphorus in the floats. McDowell (14) also found no increase in the availability of phosphate in finely ground rock phosphate by composting the mineral with cow and horse manure. Tottingham and Hoffmann (26), following the same line of investigation as that which McDowell observed, actually found a decrease in water-soluble phosphorus, but the results were similar with acid phosphate.

Krober (12) was unable to find any increase in availability of mineral phosphates by composting with sawdust and allowing fermentation to proceed. Truog (27) believes that fermented manure has a slightly solvent action on crude phosphate. He also points out that a uniform distribution of the phosphate in the soil will give much better results than that poorly distributed.

Krober (12) shows that the acid-forming bacteria and yeasts are of great value in rendering some of the phosphorus in insoluble phosphate

available. He makes the statement that carbon dioxid was more active than other acids in this respect.

The degree of fineness plays an important part in the availability of the crude phosphates. Jordan (11) proves this quite conclusively. He procured better results from the phosphates which were ground to an impalpable powder. Analysis of the plants showed an increase in the proportion of dry matter to phosphorus as the size of the particles decreased. Voelcker (29) in some of the earliest work says that the efficiency of insoluble calcium phosphate depends upon the minuteness of division; the finer the particles the more energetic will be its action.

EXPERIMENTAL WORK

MEDIUM FOR PLANT GROWTH

Pure white sand was used throughout these experiments as a medium for plant growth. For most of the work this material was leached with a dilute solution of hydrochloric acid for three days to insure the removal of plant food. The sand was then washed with distilled water until there was no trace of acid in the drainage solution. Next it was placed on clean paper until dry, when it was sifted, in order that foreign particles might be removed. Samples were collected for a phosphorus determination from each lot of sand washed, but in no case during the progress of the study was the slightest trace of phosphorus detected.

POTS

Two sizes of pots were used in this investigation. When it was necessary to grow the crop to maturity, the small glass battery jars, approximately 6 inches in diameter and 8 inches in height, proved very satisfactory; but when a grain crop was desired, the 4-gallon stone pots were more suitable. All jars were supplied with adequate drainage.

For the cultures grown in the winter the pots were covered with a coat of black paint, but for the summer series a white coat was placed over the black. The black paint prevented the growth of algæ and the white had a tendency to keep the temperature from becoming excessive within the jars. This precaution was clearly justified, for upon several occasions there was a difference of 5° to 10° in temperature between the black and white pots.

KINDS OF CROPS GROWN

Wheat, oats, rye, barley, timothy, cowpeas, soybeans, clover, and alfalfa—nine common crops that are cultivated on Illinois farms—were grown under various treatments for this investigation. High-grade seed from the previous season's crop was selected for planting, and in all cases the grains were treated with a solution of formalin to prevent smut.

In planting the seed special care was exercised in order to obtain a perfect stand, and in only a few instances was there a failure to get the proper number of plants for each pot. It seems in keeping with accurate methods of research to plant more seeds per pot than would be required for a perfect stand if they all germinated. It is safer to remove the extra plants than to transplant or reseed, and the plants are more likely to be uniform if it is possible to make some choice in thinning them down. An exact record was kept of the number of seeds planted, and all those which failed to germinate were dug out.

For inoculating the legumes, nodules from the same crop as the plant to be infected were crushed and placed in 1 liter of distilled water, and 10 c. c. of this solution were applied to the zone nearest the seed. If the nodules were not available, 300 gm. of soil from a field where the respective legumes had been grown were well shaken with 500 c. c. of water, filtered, and 10 c. c. of this solution were applied in the same manner as indicated above.

PLANT FOODS

The first application of plant food was made when the crops were planted, the others at intervals of two weeks. The plant foods were made up in the following manner:

Nitrogen: Dissolved 80 gm. of ammonium nitrate, 50 gm. of potassium sulphate, and 20 gm. of magnesium sulphate each in 2,500 c. c. of distilled water, and 0.1 gm. of ferric chlorid in 250 c. c. of distilled water. A standard application of these plant foods was 10 c. c. of each of the first three and 1 c. c. of the last diluted as desired. In no case was the solution applied in a concentrated form.

MOISTURE SUPPLY

Throughout the first period of these experiments, the water content of the sand was maintained at 14 per cent by weighing the jar each week. This phase of the details became so burdensome that it was omitted. The method was not accurate, at least during the latter period of growth, because of the irregularity in plant development due to different treatments. Some pots gave off more than 10 times the quantities transpired from others. Satisfactory results were obtained by watering the pots when they needed a supply of moisture and no difficulty was experienced in determining the point where the water content of the sand was below normal.

Whenever weather conditions would permit, the pot cultures were placed on trucks and removed to the cage out of doors.

TIME OF HARVESTING AND HANDLING THE CROP

The time of harvest was governed largely by the condition of the experiment. However, in most instances the same factors which control the time of harvest in general farm practice held true here. The grain

crops developed to full maturity, while the clover and alfalfa were cut for hay. Cowpeas and soybeans grown during the winter months were cut for hay, but those planted in the spring produced a seed crop.

Complete data on time of blooming, time of heading, number of plants, number of stems, and height of plants were collected for a comparison which might be of value in interpreting results, although such records will be omitted from this paper. The total weight of grain and straw, together with photographs, will suffice for drawing conclusions.

After harvesting the pot cultures, the materials were suspended in cheesecloth bags from the roof of the greenhouse for a period of two weeks. This was sufficient time for the product to come to a constant air-dried condition. Usually two weighings at an interval of two days were made as a check to insure accurate results.

ANALYSIS

The plants were first cut fine and then ground in a steel mill until the particles would pass a sieve of 80 meshes to the inch. Next, the materials were thoroughly mixed and samples taken for analytical purposes.

The method for the determination of phosphorus was essentially the Pemberton outline, with slight modifications.

Two gm. of the sample [1] were weighed out and moistened with calcium acetate. The sample was then dried in an electric oven and afterwards transferred to a muffle and there remained until the product was burned to a white ash. The ash was taken up with 5 c. c. of nitric acid and heated on a water bath for several minutes. It was necessary to filter to remove any silica present. From this point the regular procedure followed in the volumetric method was observed.

The mineral phosphates used in this investigation represent six types from different sections of the United States and Canada. The total phosphorus and the phosphorus soluble in citric acid are reported in Table I.

TABLE I.—*Total phosphorus and citric-acid-soluble phosphorus in various kinds of rock phosphate* [2]

Kinds of phosphate.	Phosphorus.	
	Total.	Soluble in citric acid.
Tennessee brown rock phosphate	12.75	9.92
Tennessee blue rock phosphate	13.40	10.29
Utah rock phosphate	13.81	8.66
South Carolina land rock phosphate	13.75	6.89
Florida soft rock phosphate	13.98	10.55
Canadian apatite	12.75	5.57

[1] Two gm. was satisfactory for straw and hay, but for the grain ¼ gm. was sufficient.

[2] Four gm. of each of the mineral phosphates were placed in a 1-liter flask and then 1,000 c. c. of a 0.2 per cent solution of citric acid was poured on the ground rock, where it remained for 48 hours with occasional shaking. Then some of the solution was filtered and 100 c. c. of the filtrate taken for analysis.

AVAILABILITY OF THE PHOSPHORUS IN TENNESSEE BROWN ROCK PHOSPHATE

This series comprises a study of the ability of different crops to secure phosphorus for growth from Tennessee brown rock phosphate without the aid of decaying organic matter. The literature indicates rather clearly that crops differ widely in this respect, but there is but very little direct information from trials conducted under controlled conditions where sand was used as a substitute for soil. The suggestion has been made, also, that there is slight increase in the yield with large application of phosphate. The object of the series reported in Tables II to VI is to present new information on these two important points.

The pots used were the large, glazed 4-gallon jars into which could be placed 22,000 gm. of sand (Pl. LXXIII, LXXIV, LXXV). In this case the sand was not leached with dilute acid, but was washed for several days with distilled water. The rock phosphate was ground sufficiently fine to pass through a sieve of 100 meshes to the inch. On March 20, 1914, the pots were seeded; and after the plants had made satisfactory growth, they were thinned to 15 to each jar.

TABLE II.—*Dry matter and phosphorus content of plant products from wheat and oats*

SERIES 1A; SPRING WHEAT HARVESTED ON JUNE 29, 1914[a]

Pot No.	Phosphate added.	Grain.	Straw.	Phosphorus.					
				Grain.	Straw.	Grain.	Straw.	Total in grain and straw.	Percentage removed.
	Gm.	*Gm.*	*Gm.*	*Per cent.*	*Per cent.*	*Mgm.*	*Mgm.*	*Mgm.*	
1....	0	0	6.0	....	....	....	....	....	....
2....	0	0	6.5	....	....	....	....	....	....
3....	11	1.0	16.0	....	....	....	....	....	....
4....	11	1.4	19.1	0.260	0.038	3.64	7.26	10.90	0.78
5....	22	4.1	21.9	....	....	....	....	....	....
6....	22	4.0	20.6	.257	.029	10.31	6.06	16.37	.58
7....	66	12.7	39.3	....	....	....	....	....	....
8....	66	12.8	35.9	.240	.019	30.72	6.64	37.36	.44
9....	220	17.5	42.9	....	....	....	....	....	....
10...	220	16.8	40.4	.335	.026	56.20	10.30	66.50	.24
SERIES 1B; SIXTY-DAY OATS HARVESTED ON JUNE 7, 1914[b]									
11...	0	0	6.0	....	....	....	....	....	....
12...	0	0	6.1	....	.035	....	2.14	2.14	....
13...	11	4.7	10.0	....	....	....	....	....	....
14...	11	4.5	10.7	0.184	.038	8.28	4.11	12.38	.88
15...	22	7.6	13.6	.189	.032	14.36	4.35	18.72	.67
16...	22	7.2	14.0	....	....	....	....	....	....
17...	66	10.9	18.6	....	....	....	....	....	....
18...	66	12.1	15.4	.229	.038	27.71	5.85	33.56	.40
19...	220	16.8	22.9	....	....	....	....	....	....
20...	220	14.3	20.0	.354	.059	50.62	11.80	62.42	.22

[a] Seed planted in each pot in series 1A contained 0.46 per cent of phosphorus. Fifteen seeds contained 1.7 mgm. of phosphorus.

[b] Seed planted in each pot in series 1B contained 0.35 per cent of phosphorus. Fifteen seeds contained 1.29 mgm. of phosphorus.

TABLE III.—*Dry matter and phosphorus content of plant products from timothy and red-clover hay*

SERIES IE; TIMOTHY HARVESTED ON JULY 21, SEPT. 26, AND NOV. 25, 1914

Pot No.	Phosphate added.	Crop.			Phosphorus.					
		First cutting.	Second cutting.	Third cutting.	First cutting.	Second cutting.	First cutting.	Second cutting.	Total, two crops.	Percentage removed.
	Gm.	*Gm.*	*Gm.*	*Gm.*	*Per cent.*	*Mgm.*	*Per cent.*	*Mgm.*	*Mgm.*	
41....	0	0.5	1.0	1.8	......	......	......	......	......	......
42....	0	.8	.6	1.5	......	......	......	......	......	......
43....	11	11.8	8.6	4.3	......	......	......	......	......	......
44....	11	12.8	7.1	4.5	......	......	......	......	......	......
45....	22	17.2	10.0	6.0	0.067	0.102	11.52	10.15	21.67	0.77
46....	22	17.1	9.6	6.0	......	......	......	......	......	......
47....	66	27.5	26.0	7.9	......	......	......	......	......	......
48....	66	28.0	25.6	8.0	......	......	......	......	......	......
49....	220	31.6	28.0	8.2	[a].126	.170	37.80	49.98	87.78	.31
50....	220	27.7	30.8	8.7	......	......	......	......	......	......

SERIES IH; RED-CLOVER HAY HARVESTED ON JULY 20, SEPT. 26, DEC. 25, 1914

71....	0	.4	.2	.1	......	......	......	......	......	......
72....	0	.3	.1	.1	......	......	......	......	......	......
73....	11	5.1	3.5	3.4	......	......	......	......	......	......
74....	11	4.0	2.8	3.5	......	......	......	......	......	......
75....	22	7.8	12.2	8.4	.041	.055	3.23	6.73	9.967	.36
76....	22	9.0	12.8	8.7	......	......	......	......	......	......
77....	66	16.2	23.0	13.3	......	......	......	......	......	......
78....	66	20.8	24.1	13.0	......	......	......	......	......	......
79....	220	42.8	36.5	[b]10.0	.169	[c].215	72.55	78.29	150.839	.54
80....	220	54.5	37.8	14.2	......	......	......	......	......	......

[a] The phosphorus content of average timothy hay is 0.09 per cent.
[b] Attacked by worms.
[c] The phosphorus content of average red-clover hay is about 0.21 per cent.

TABLE IV.—*Dry matter and phosphorus content of plant products from cowpeas and soybeans*

SERIES IF; COWPEAS HARVESTED ON JULY 6, 1914

Pot No.	Phosphate added.	Grain.	Straw.	Phosphorus.					
				Grain.	Straw.	Grain.	Straw.	Total in grain and straw.	Percentage removed.
	Gm.	*Gm.*	*Gm.*	*Per cent.*	*Per cent.*	*Mgm.*	*Mgm.*	*Mgm.*	
51........	0	0	2.8	......	......	......	......	......	......
52........	0	0.3	2.7	......	0.073	......	1.97	1.97	......
53........	11	0.7	4.3	......	......	......	......	......	......
54........	11	0	4.9	......	.095	......	4.66	4.66	......
55........	22	1.4	7.6	0.273	.097	3.82	7.37	11.19	0.40
56........	22	0.7	6.7	......	......	......	......	......	......
57........	66	11.7	23.8	.300	.117	35.08	27.92	62.99	.75
58........	66	12.1	27.6	......	......	......	......	......	......
59........	220	12.1	22.5	......	......	......	......	......	......
60........	220	14.1	30.9	[a].297	.128	41.86	39.40	81.26	.29

[a] Seed planted in each pot contained 0.434 per cent of phosphorus. Fifteen cowpea seeds contained 11.7 mgm. of phosphorus.

TABLE IV.—*Dry matter and phosphorus content of plant products from cowpeas and soybeans*—Continued.

SERIES 1G; SOYBEANS HARVESTED ON JUNE 10, 1914

Pot No.	Phosphate added.	Grain.	Straw.	Phosphorus. Grain.	Phosphorus. Straw.	Phosphorus. Grain.	Phosphorus. Straw.	Phosphorus. Total in grain and straw.	Phosphorus. Percentage removed.
	Gm.	*Gm.*	*Gm.*	*Per cent.*	*Per cent.*	*Mgm.*	*Mgm.*	*Mgm.*	
61	0	1.0	9.0	......	......	......	......	......	......
62	0	1.0	8.3	0.360	0.058	3.60	4.77	8.37	......
63	11	2.0	9.2	......	......	......	......	......	......
64	11	2.8	10.2	.359	.045	10.06	4.54	14.60	1.04
65	22	3.5	13.5	......	......	......	......	......	......
66	22	2.4	10.8	.448	.062	10.76	6.64	17.40	.62
67	66	2.9	14.9	......	......	......	......	......	......
68	66	3.4	15.3	.449	.061	15.25	9.38	24.63	.29
69	220	4.7	15.2	......	......	......	......	......	......
70	220	4.2	13.4	[a].448	.088	18.83	11.83	30.66	.11

[a] Seed planted in each pot contained 0.6 per cent of phosphorus. Fifteen soybean seeds contained 11.9 mgm. of phosphorus.

TABLE V.—*Dry matter and phosphorus content of plant products from alfalfa harvested on June 4, July 18, Sept. 26, and Nov. 11, 1914—series 1I*

Pot No.	Phosphate added.	First cutting.	Second cutting.	Third cutting.	Fourth cutting.	Phosphorus.[a] First cutting.	Phosphorus. Second cutting.	Phosphorus. Third cutting.	Phosphorus. First cutting.	Phosphorus. Second cutting.	Phosphorus. Third cutting.	Phosphorus. Total, three cuttings.	Phosphorus. Percentage removed from pots.
	Gm.	*Gm.*	*Gm.*	*Gm.*	*Gm.*	*Per ct.*	*Per ct.*	*Per ct.*	*Mgm.*	*Mgm.*	*Mgm.*	*Mgm.*	*Per ct.*
81	0	0.3	0.2	0.5	0.4	......	......	......	......	......	......	......	......
82	0	.3	.2	.6	.4	......	......	......	......	......	......	......	......
83	11	5.5	8.9	13.0	6.0	......	......	......	......	......	......	......	......
84	11	7.1	9.0	12.7	6.5	0.17	0.19	0.18	22	25	22	69.9	2.49
85	22	13.0	13.0	12.5	5.0	......	......	......	......	......	......	......	......
86	22	11.0	11.0	[b] 10.0	5.5	......	......	......	......	......	......	......	......
87	66	13.6	13.9	18.6	10.2	......	......	......	......	......	......	......	......
88	66	13.6	12.8	16.5	10.1	......	......	......	......	......	......	......	......
89	220	18.6	19.9	20.0	10.7	.10	.26	.28	17	51	55	124.6	.44
90	220	17.1	15.6	16.0	10.0	......	......	......	......	......	......	......	......

[a] Alfalfa hay contains 0.0172 per cent of phosphorus. [b] Attacked by worms.

TABLE VI.—*Dry matter produced by spring rye and barley—series 1C*

Pot No.	Rye. Phosphate added.	Rye. Grain.	Rye. Straw.	Pot No.	Barley. Phosphate added.	Barley. Grain.	Barley. Straw.
	Gm.	*Gm.*	*Gm.*		*Gm.*	*Gm.*	*Gm.*
21	0	0	1.9	31	0	0	8.7
22	0	0	1.8	32	0	0	7.2
23	11	0	10.9	33	11	2.6	20.3
24	11	0	11.6	34	11	1.3	16.4
25	22	0	22.2	35	22	2.0	17.8
26	22	0	21.0	36	22	8.5	22.3
27	66	0	37.0	37	66	5.0	23.3
28	66	0	38.2	38	66	14.2	23.4
29	220	0	45.1	39	220	20.9	34.8
30	220	0	42.0	40	220	16.5	28.0

Probably the most striking point shown by Tables II to VI is the gradual increase in the yield of both grain and straw from wheat, oats, and barley and in the hay from rye and timothy. In all cases larger applications of phosphorus gave higher returns, though not always in the same degree.

The grain yield of wheat is especially interesting. Eleven gm. of Tennessee brown rock phosphate produced 1.2 gm. of grain, while double this application produced 4.05 gm., or almost four times the yields from the light-application pots. Pots 7 and 8, which received 6 times as much phosphorus as pots 3 and 4, produced approximately 11 times as much wheat. Pots 9 and 10 received 20 times as much phosphorus as pots 3 and 4, but gave in return only about 14 times as much grain. Scarcely more evidence is necessary to show that wheat is able to take its phosphorus supply from Tennessee brown rock phosphate. It is also evident that the rate of yield is to a certain degree dependent upon the rate of application of the fertilizer. In the case of the heavy application, there were indications that the size of the pot was a limiting factor.

Oats responded more uniformly to the phosphate application than did wheat. The average yield of grain for pots 13 and 14 was 4.6 gm.; pots 15 and 16, which received double the quantity of phosphorus supplied to pots 13 and 14, yielded less than twice the amount of grain. For the highest application there is still a larger difference in the phosphorus applied and the crop produced, due, no doubt, to the limited size of the pot. The yield of straw followed about the same rate of increase as the grain.

Spring rye was not able to endure the heat of the summer days, and at the time of harvest growth had almost ceased without producing a single grain. The hay yield shows a gradual increase in dry matter as the application of phosphate rock was increased.

The yields from barley are not so consistent as those reported for wheat and oats. However, in all probability the same uniformity would have resulted had the crop not been attacked by smut. Although pots 34, 35, 37, 38, and 39 were badly affected, there was a gradual increase in grain and straw as the application of phosphorus increased. A yield of even 18 bushels for barley is not altogether unsatisfactory.

The data on timothy are no less interesting than those on the growth of the cereals, because of the opportunity to study the yields of the various cuttings. Timothy displays the same tendency to produce larger returns for greater quantities of phosphorus applied to the sand. For each pot there was a gradual decrease from the first to the last cutting, although the drop was less abrupt between the first and second than between the third and fourth cuttings.

Contrary to what might be expected the legumes respond to phosphate treatment no better than do the cereals. Perhaps on the whole this latter group produced larger gains than the former.

The results from the cowpeas show some points of particular interest. There was scarcely any seed produced for the pots to which 11 and 22 gm. of raw rock had been applied, but there was a decided increase for the pots which received 66-gm. applications. The next treatment, which was 220 gm. per pot, showed a slight increase, approximately 3 bushels per acre. For the cowpea hay the results are very similar to the seed yield. There is not a very marked increase in the hay production until the larger applications are made. The pots which received 66 gm. produced nearly as much hay as the pots which received 220 gm. of rock phosphate.

Cowpeas do not give results that correspond with those from soybeans. In the first place, the no-treatment pots produced a significant quantity of soy-bean seed, the yield on the acre basis amounting to 2.64 bushels, while the returns from the pots receiving the largest application just about quadrupled those from the former. The ratios for the yields of hay are about the same as for the grain. The yields for both seed and hay in the case of soybeans are unsatisfactory, which is not true of the cowpeas. It would seem that the latter legume utilizes rock phosphate better than soybeans.

To the practical agriculturist the returns from red clover will prove of considerable interest. It will be observed that the lowest treatment, 11 gm. per pot, produced hay at the rate of 772 pounds per acre. With double the application a little less than the former yield is recorded. When the lowest application is increased to six times the original amount, the yield of hay is increased about three times. The largest application, which was 20 times that of the lowest, produced practically 10 times as much hay as the first treatment. The above figures are for the first cutting only.

For the second harvest the relative yields of the 22- and 66-gm. treatments are more satisfactory than for the first cutting. It will be observed that the yield of the pots with 11-gm. applications and those with the 220-gm. applications hold the same relation for the second cutting as for the first. No direct comparison for the third cutting should be made, because pot 79, just previous to cutting, was attacked during a single night by a large cutworm which did considerable damage to the growing crop. It is true, however, that there had not been as much difference in the growth on the high-treatment pot as had been observed earlier in the season. The total yield for three cuttings for the heaviest application is large, but it can hardly be said that the pots which received 22 gm. of rock phosphate produced unprofitable yields.

Because of its extensive root system alfalfa would be expected to produce greater yields than clover. However, the difference in this experiment is not so marked. From four cuttings of alfalfa the yield of hay from the lowest treatment was 5,451 pounds, as against 1,819 pounds

of clover from the same treatment for three cuttings. For the next higher treatment the comparison is 6,426 pounds of alfalfa to 4,674 pounds of clover. The yields are approximately the same for the third application, but for the heavy treatment the clover almost doubles the yield from the alfalfa. Special attention is called to Plates LXXIII, LXXIV, and LXXV.

In drawing conclusions from an investigation of this kind the actual growth of the plant must be regarded as a most significant factor. However, an analytical study of the crops harvested can not fail to be of great value. Since phosphorus is the element with which this paper chiefly concerns itself, quantitative determinations were confined to that substance.

The determinations show that in practically all cases phosphorus is the limiting element in production. In every instance the dry matter increased as the phosphorus content of the pot was increased; also the quantity of phosphorus assimilated increased as the dry matter increased. The percentage of phosphorus in the plant in the majority of cases increased as the application of raw rock grew larger. This is especially noticeable in the hay crop. The most notable exceptions were observed in wheat and oat straw. There is no definite relation in the quantity of phosphorus applied and the percentage assimilated by the crop. There was a slight tendency in the grain for the percentage removed to decrease as the application was increased, but for the legumes this ratio does not hold. As high as 2.49 per cent of the phosphorus supplied in raw rock phosphate was removed in one season's growth of alfalfa.

COMPARATIVE STUDY OF THE PRODUCTIVE POWERS OF SIX MINERAL PHOSPHATES

The results from Tennessee brown rock phosphate proved so interesting that it was planned to determine the comparative value of mineral phosphates from the various mines of America. For this purpose Tennessee brown rock phosphate, Tennessee blue rock phosphate, South Carolina land rock phosphate, Utah rock phosphate, Canadian apatite, and Florida soft rock phosphate were selected.

The materials were ground so that all particles would pass through a sieve with 100 meshes to the inch and were applied in quantities which contained equal amounts of phosphorus for a given set of pots. Clover, oats, and cowpeas were grown with these different phosphates.

Because of limited space the small battery jars into which could be placed conveniently 4,800 gm. were selected for this rather extensive trial. Without crowding, eight plants per pot could be grown (Pl. LXXVI). Table VII gives the quantity of the phosphate applied and the yields of the crops in question. The planting was done on October 3, 1914, and the crops of clover were harvested on March 5 and April 9, 1915, while the oats were cut on February 5, 1915.

TABLE VII.—*Dry matter produced by different kinds of mineral phosphates—series 2*

Kind of phosphate added.	Red clover.				Sixty-Day oats.		
	Pot No.	Quantity of phosphate.	First cutting.	Second cutting.	Pot No.	Phosphate added.	Yield of straw.
		Gm.	*Gm.*	*Gm.*		*Gm.*	*Gm.*
None	1	0	0	0	39	0	1.1
Do	2	0	0	0	40	0	1.0
Tennessee brown rock	3	1.81	2.7	1.9	41	1.81	4.4
Do	4	1.81	1.0	.5	42	1.81	3.3
Do	5	3.62	4.3	3.3	43	3.62	5.7
Do	6	3.62	4.3	3.8	44	3.62	4.2
Do	7	10.86	7.1	4.8	45	10.86	6.9
Do	8	10.86	6.1	4.9	46	10.86	6.7
Canadian apatite	9	1.81	0	0	47	1.81	1.1
Do	10	1.81	0	0	48	1.81	1.1
Do	11	3.62	0	0	49	3.62	1.1
Do	12	3.62	0	0	50	3.62	1.3
Do	13	10.86	0	0	51	10.86	2.3
Do	14	10.86	0	0	52	10.86	1.4
South Carolina land rock	15	1.68	.2	1.3	53	1.68	2.2
Do	16	1.68	3.3	3.8	54	1.68	2.0
Do	17	3.36	.9	.8	55	3.36	1.3
Do	18	3.36	1.2	1.8	56	3.36	2.2
Do	19	10.07	1.1	0	57	10.07	3.4
Do	20	10.07	0	0	58	10.07	2.0
Utah rock	21	1.67	1.8	4.9	59	1.67	2.0
Do	22	1.67	3.4	5.0	60	1.67	1.4
Do	23	3.34	3.3	3.0	61	3.38	1.2
Do	24	3.34	0	0	62	3.38	1.9
Do	25	10.01	2.2	3.7	63	10.01	1.2
Do	26	10.01	2.9	4.7	64	10.01	1.5
Tennessee blue rock	27	1.72	0	0	65	1.72	1.6
Do	28	1.72	0	0	66	1.72	1.4
Do	29	3.44	.9	1.5	67	3.44	3.0
Do	30	3.44	.3	1.8	68	3.44	3.3
Do	31	10.33	7.0	6.7	69	10.33	3.3
Do	32	10.33	5.6	7.6	70	10.33	3.4
Florida soft rock	33	1.65	5.0	5.1	71	1.65	1.5
Do	34	1.65	3.5	5.1	72	1.65	1.2
Do	35	3.30	6.1	5.0	73	3.30	1.9
Do	36	3.30	4.4	5.9	74	3.30	1.9
Do	37	9.90	5.8	7.0	75	9.90	3.0
Do	38	9.90	5.8	6.9	76	9.90	3.2

In the foregoing series the greatest contrast is shown by the clover in its response to Tennessee brown rock phosphate and Canadian apatite. With brown rock the yield advanced rapidly with each increase in the amount of phosphate applied; but apatite, even with repeated plantings, failed to produce growth. South Carolina land rock phosphate proved better than apatite, but the growth for this treatment was very irregular. Utah phosphate excelled the South Carolina land rock phosphate. Except for

the lowest treatment, Tennessee blue phosphate gave fairly satisfactory yields. Florida phosphate for the three treatments gave almost as good returns as the Tennessee brown rock. Attention is called to the comparative yields of the Florida rock for the lowest and highest treatments. In this case a smaller quantity of the soft phosphate gave almost as large returns as the greater supply.

TABLE VIII.—*Dry matter produced by different kinds of mineral phosphate in red clover and Sixty-Day oats—series 3*

Kind of phosphate added.	Red clover.			Sixty-Day oats.			
	Pot No.	Phosphate.	Yield of hay.	Pot No.	Phosphate.	Grain.	Straw.
		Gm.	*Gm.*		*Gm.*	*Gm.*	*Gm.*
None	1	0	0.1	43	0	0.1	1.1
Do	2	0	.1	44	0	.1	1.1
Tennessee brown rock	3	11	1.0	45	11	.2	5.3
Do	4	11	1.0	46	11	1.4	5.4
Do	5	22	2.0	47	22	3.2	9.5
Do	6	22	2.0	48	22	3.0	8.2
Do	7	66	3.9	49	66	5.3	10.3
Do	8	66	4.1	50	66	5.2	9.0
Do	9	220	3.8	51	220	3.8	13.0
Do	10	220	4.0	52	220	5.0	12.0
Canadian apatite	11	11	.1	53	11	0	1.4
Do	12	11	.1	54	11	0	1.4
Do	13	22	.2	55	22	0	1.4
Do	14	22	.2	56	22	0	1.6
Do	15	66	.1	57	66	0	1.3
Do	16	66	.3	58	66	0	1.0
Do	17	220	.1	59	220	0	1.2
Do	18	220	.1	60	220	0	1.5
Utah rock	19	10.11	.2	61	10.11	0	.8
Do	20	10.11	.2	62	10.11	0	.8
Do	21	20.22	.7	63	20.22	0	.8
Do	22	20.22	.5	64	20.22	0	1.3
Do	23	60.66	.5	65	60.66	0	.9
Do	24	60.66	.4	66	60.66	0	.9
Do	25	202.20	.2	67	202.20	0	.9
Do	26	202.20	.1	68	202.20	0	.9
South Carolina land rock	27	10.16	.1	69	10.16	0	1.0
Do	28	10.16	.1	70	10.16	0	.8
Do	29	20.32	.1	71	20.32	0	.9
Do	30	20.32	.1	72	20.32	0	.9
Do	31	60.96	.1	73	60.96	0	.7
Do	32	60.96	.1	74	60.96	0	.8
Do	33	203.20	.1	75	203.20	0	.6
Do	34	203.20	.1	76	203.20	0	.5
Tennessee blue rock	35	10.42	.2	77	10.42	0	.9
Do	36	10.42	.2	78	10.42	0	1.0
Do	37	20.84	.3	79	20.84	0	.9
Do	38	20.84	.1	80	20.84	0	.7
Do	39	62.52	.4	81	62.52	0	.8
Do	40	62.52	.5	82	62.52	0	.9
Do	41	208.40	.3	83	208.40	0	1.0
Do	42	208.40	.6	84	208.40	0	.9

Under greenhouse conditions it was extremely difficult to secure a seed crop of oats during the winter months; hence, the differences of productive power of the various phosphates must be measured by the yields of straw. In a general way the results obtained in this manner are in harmony with those reported for clover. The brown rock excelled the other phosphates in the production of hay; blue phosphate ranks second; and where apatite was applied it will be observed that the plants made very little growth. Plate LXXVI indicates greater difference in the growth of clover than the dry weight of the top.

The above data indicate that there was an increase in yield as the quantity of phosphorus was increased. The question naturally arises as to the point at which larger applications of rock phosphate failed to produce greater returns. In order to answer this query, the following results are inserted (Table VIII): The lowest treatment in the table is about the same as the highest application in series two. This set of pot cultures was planted on August 27, 1914, and harvested on December 4, 1914.

By referring to the clover in Table VIII, a comparison of the yields shows nothing particularly in favor of excessive quantities of rock phosphate. One point, however, is of interest, and that is that the oats produced a seed crop on the land with the heavy application of brown rock. The hay on the other pots was scarcely more than could be produced by the phosphorus in the seeds planted.

TABLE IX.—*Dry matter produced by various kinds of mineral phosphates in cowpeas, series 3*

Kind of phosphate added.	Pot No.	Phosphate.	Yield of hay.	Kind of phosphate added.	Pot No.	Phosphate.	Yield of hay.
		Gm.	*Gm.*			*Gm.*	*Gm.*
None	1	0	1.0	Utah rock	22	20.22	2.2
Do	2	0	0.9	Do	23	60.66	1.4
Tennessee brown rock	3	11	1.1	Do	24	60.66	1.4
Do	4	11	1.9	Do	25	202.20	.9
Do	5	22	4.6	Do	26	202.20	.9
Do	6	22	4.5	South Carolina land rock	27	10.16	2.0
Do	7	66	11.9	Do	28	10.16	2.2
Do	8	66	10.7	Do	29	20.32	6.4
Do	9	220	17.4	Do	30	20.32	5.4
Do	10	220	13.9	Do	31	60.96	4.7
Canadian apatite	11	11	1.0	Do	32	60.96	4.5
Do	12	11	1.0	Do	33	203.20	.9
Do	13	22	1.0	Do	34	203.20	1.5
Do	14	22	1.0	Tennessee blue rock	35	10.42	4.0
Do	15	66	1.6	Do	36	10.42	3.5
Do	16	66	1.3	Do	37	20.84	4.7
Do	17	220	.9	Do	38	20.84	5.0
Do	18	220	.9	Do	39	62.52	3.9
Utah rock	19	10.11	2.0	Do	40	62.52	4.2
Do	20	10.11	2.9	Do	41	208.40	1.9
Do	21	20.22	3.4	Do	42	208.40	2.1

Soon after the clover was harvested in series 3, these pots were seeded to cowpeas. Cowpeas were planted to determine the ability of this legume to utilize the phosphorus contained in mineral phosphates. The cultures were seeded January 24, 1914, and harvested April 5, 1914 (Table IX).

The results secured for series 4 are in accord with those from the clover and oats grown on the pots with large applications. The pots to which had been added brown rock phosphate produced a good return of cowpea hay after having given satisfactory yields of clover.

The data presented in the previous tables show conclusively that certain species of plants have the power to obtain phosphorus from brown rock phosphate, but how they acquire this element is the problem of vital concern. Do they secure their phosphorus without indirect aid and what influence do other plant foods applied in a soluble form exert on the phosphorus compounds?

It will be remembered that the sand cultures were maintained at a moisture content of 14 per cent. The plant food application, the infusion, and the water added when the seeds were planted constituted the first moisture supply; or, in other words, all these solutions brought the water content up to 14 per cent. In most of the cases five applications of plant food were sufficient to produce a crop of clover or oats.

To estimate the influence of water and plant-food solutions on the solubility of the phosphates, quantities of raw rock which correspond to the smallest application (1.81 gm.), soluble plant food equivalent to five applications, and water sufficient to bring the supply of the solution to the same amount that was necessary to bring the moisture content to 14 per cent, or 672 c. c., were placed in a 1-liter flask and shaken each day for three months. The soluble phosphorus was then determined with the results shown in Table X.

TABLE X.—*The influence of soluble plant foods on the solubility of the phosphorus in mineral phosphates*

Material applied and pot No.	Kind of phosphate.	Quantity of phosphate.	Phosphorus dissolved.
Water only:		*Gm.*	*Mgm.*
1	Tennessee brown rock	1.81	0.25
Water and soluble plant food:			
2	do	1.81	.33
3	Tennessee blue rock	1.72	.05
4	Canadian apatite	1.81	.05
5	South Carolina land rock	1.68	.056
6	Utah rock	1.67	.14
7	Florida soft rock	1.65	.28

The solutions dissolve very little of the phosphorus from the insoluble phosphate.

Brown rock phosphate and Florida soft rock phosphate gave the best results with clover, but the former was very much better suited for oats than the latter. There is a slight indication that phosphates which are more soluble in water are more easily assimilated by plants.

THE INFLUENCE OF FERMENTING DEXTROSE AND CROP RESIDUES ON THE AVAILABILITY OF PHOSPHORUS IN FINELY GROUND ROCK PHOSPHATE

Though the data are not conclusive, a large number of field experiments conducted in America show that raw phosphate, when applied in conjunction with organic matter, produces very appreciable increases in crop yields. The work which follows is an effort to determine the influence of decaying substances on the availability of the phosphorus in crude phosphate rock. Dextrose was employed because it ferments rapidly under greenhouse conditions. Crop residues are also included in this section, but owing to the slow growth of crops through the winter months it will not be possible to do more than to make a preliminary report on this phase of the problem.

Throughout the study included in this division, the glass battery jars were utilized with success and the same quantity of sand employed as previously noted—namely, 4,800 gm. per pot. For all the cultures grown in the dextrose section, the sand was leached with dilute hydrochloric acid.

The first series reported below was outlined primarily to secure data on the value of rock phosphate alone and in conjunction with dextrose for rye and clover. It will be observed that the applications of the rock phosphate and the dextrose were made on the percentage basis. In order to hasten fermentation, an infusion from a rich soil was a part of the treatment. This series was planted on April 12, 1913, and harvested on August 19, 1913.

Since dextrose applied at the rate of 48 gm. per pot injured the rye and destroyed the clover, a point of importance to decide was what quantity would not injure plant development, but would assist in the liberation of phosphorus. With this point in mind, series 6 was planned. The planting was done on June 21, 1913, and the crop harvested on December 1, 1913. (See Table XI.)

The dextrose in series 5 had no beneficial influence. If the average of pots 7, 8, and 9 is compared with the results from either set of pots 1, 2, and 3 or pots 4, 5, and 6, it will be evident that the dextrose is harmful. Clover failed to make growth where the dextrose was added, but did fairly well on the pots which received rock phosphate alone.

The data in Table XI show that dextrose fails to be of any particular advantage for rendering phosphorus available for the growth of rye and clover. Even small quantities of this material killed clover.

TABLE XI.—*Dry matter produced by Tennessee brown rock phosphate and dextrose in growing spring rye and red clover*

SERIES 5

Rye.					Red clover.				
Pot No.	Phosphate added.	Dextrose added.	Infusion added.	Hay yield.	Pot No.	Phosphate added.	Dextrose added.	Infusion added	Hay yield.
	Gm.	*Gm.*	*C. c.*	*Gm.*		*Gm.*	*Gm.*	*C. c.*	*Gm.*
1....	48	48	0	22.9	19...	48	48	20	[a] 0
2....	48	48	0	33.9	20...	48	48	20	[a] 0
3....	48	48	0	31.3	21...	48	48	20	[a] 0
4....	48	48	20	35.3	22...	48	0	0	3.0
5....	48	48	20	32.3	23...	48	0	0	3.8
6....	48	48	20	22.0	24...	48	0	0	2.9
7....	48	0	0	27.2					
8....	48	0	0	32.5					
9....	48	0	0	36.0					

SERIES 6

3...	48	4.8	20	14.6	17...	48	4.8	20	[b] 20
4...	48	4.8	20	17.9	18...	48	4.8	20	[b] 20
5...	48	14.4	20	17.5	19...	48	14.4	20	[b] 20
6...	48	14.4	20	16.0	20...	48	14.4	20	[b] 20
7...	48	24.0	20	16.8	21...	48	24.0	20	[b] 20
8...	48	24.0	20	20.7	22...	48	24.0	20	[b] 20
9...	48	48.0	20	14.5	23...	48	48.0	20	[b] 20
10...	48	48.0	20	11.6	24...	48	48.0	20	[b] 20
11...	48	0	20	18.7	25...	48	0	20	3.0
12...	48	0	20	17.7	26...	48	0	20	2.9
					27...	0	0	20	0
					28...	0	0	20	0

[a] The clover in pots 19, 20, and 21 was dead on June 29, 1913.
[b] The clover in pots 17 to 24, inclusive, was dead in less than 1 month after planting.

Rye and clover were replaced in series 7 (Table XII) by cowpeas, with the feeling that the latter crop might respond more readily to various treatments (Pl. LXXVII). The cowpeas were planted on July 4, 1913, and harvested on October 2, 1913.

The cowpeas grown in series 7 show clearly that so small a quantity of dextrose as 4.8 per cent was injurious to plant growth. Where dextrose was applied, smaller quantities of phosphorus were assimilated, due, no doubt, to the injury of the plant by the acids formed from decomposing dextrose. However, the percentage of phosphorus increased as the quantity of the fermentable substance was increased.

TABLE XII.—*Dry matter and phosphorus content of plant products of cowpeas from pot cultures, with the addition of Tennessee brown rock phosphate and dextrose; series 7*

Pot No.	Phosphate added.	Dextrose added.	Infusion added.	Hay yield.	Phosphorus content.		
					Hay.	Hay yield.	Removed from pot.
	Gm.	*Gm.*	*C. c.*	*Gm.*	*Per cent.*	*Mgm.*	*Per cent.*
1	48	4.8	20	25.0	0.319	79.75	1.30
2	48	4.8	20	22.3	....	....	....
3	48	14.4	20	11.9	....	....	....
4	48	14.4	20	8.8	.381	33.33	.54
5	48	24.0	20	[a] 0	....	....	....
6	48	24.0	20	[a] 0	....	....	....
7	48	48.0	20	[a] 0	....	....	....
8	48	48.0	20	[a] 0	....	....	....
9	0	48.0	20	[a] 0	....	....	....
10	0	48.0	20	[a] 0	....	....	....
11	48	0	20	29.9	....	....	....
12	48	0	20	29.1	.286	85.51	1.40
13	0	0	20	4.0	....	....	....
14	0	0	20	3.0	[b] .128	3.84	....

[a] The plants on pots 5 to 10, inclusive, were all dead by Aug. 9, 1913.
[b] Five cowpea seeds were planted in each pot. These contained 3.92 mgm. of phosphorus.

Rye, clover, and cowpeas failed to thrive wherever the smallest quantity of dextrose was present. There is but little doubt that this destructive influence is due to the decomposition of dextrose. If this conclusion be true, a liberal use of calcium carbonate should neutralize the acids developed, and a normal growth of the plants should result. Series 8 (Table XIII) was designed for determining what influence calcium carbonate would have in stimulating plant growth by producing an alkaline medium and to ascertain whether calcium served as a food.

TABLE XIII.—*Dry matter produced in spring rye by Tennessee brown rock phosphate with the addition of dextrose and calcium carbonate—series 8*

Pot No.	Phosphate added.	Dextrose added.[a]	Calcium carbonate added.	Hay yield.	Pot No.	Phosphate added.	Dextrose added.[a]	Calcium carbonate added.	Hay yield.
	Gm.	*Gm.*	*Gm.*	*Gm.*		*Gm.*	*Gm.*	*Gm.*	*Gm.*
1	48	48	10	7.2	13	0	0	0	0.5
2	48	48	10	9.3	14	0	0	0	.6
3	48	48	0	5.2	15	48	0	0	11.2
4	48	48	0	3.5	16	48	0	0	12.1
5	48	48	10	7.0	17	48	4.8	10	10.7
6	48	48	10	7.0	18	48	4.8	10	10.0
7	0	0	0	.1	19	48	4.8	0	0.6
8	0	0	0	.1	20	48	4.8	0	0.0
9	48	48	0	7.8	21	0	0	0	.4
10	48	48	0	8.9	22	0	0	0	.5
11	0	0	0	.1	23	48	48	0	6.5
12	0	0	0	.1	24	48	48	0	6.0

[a] Pots 5 and 6 were leached and the leachings placed on pots 7 and 8. Pots 9 and 10 were leached and the leachings placed on pots 11 and 12. Pots 13 and 14 received all plant food but phosphorus. Pots 21 and 22 received nothing. Pots 23 and 24 were leached and drainage water taken for analytical purposes.

Series 8 shows that dextrose in conjunction with calcium carbonate did not give as good results as raw rock phosphate alone, and that 10 gm. of calcium carbonate was not sufficient to nullify the harmful influence of the dextrose.

Series 9 (Table XIV), which follows, is just the same as series 8 except that cowpeas are substituted for rye, the object being to determine the relative response of rye and cowpeas to the different treatments.

TABLE XIV.—*Dry matter produced in cowpeas by Tennessee brown rock phosphate with the addition of dextrose and calcium carbonate—series 9*

Pot No.	Phosphate added.	Dextrose added.	Calcium carbonate added.	Hay yield.	Pot No.	Phosphate added.	Dextrose added.	Calcium carbonate added.	Hay yield.
	Gm.	*Gm.*	*Gm.*	*Gm.*		*Gm.*	*Gm.*	*Gm.*	*Gm.*
1F..	48	48	10	5.5	13F..	0	0	0	3.3
2F..	48	48	10	5.3	14F..	0	0	0	3.0
3F..	48	48	0	5.2	15F..	48	0	0	12.4
4F..	48	48	0	4.0	16F..	48	0	0	14.5
5F..	48	[a] 48	10	5.3	17F..	48	4.8	10	8.1
6F..	48	48	10	6.1	18F..	48	4.8	10	10.1
7F..	0	0	0	3.8	19F..	48	4.8	0	11.1
8F..	0	0	0	3.8	20F..	48	4.8	0	11.8
9F..	48	48	0	4.2	21F..	0	0	0	3.9
10F..	48	48	0	3.0	22F..	0	0	0	4.5
11F..	0	0	0	3.1	23F..	48	48	0	4.0
12F..	0	0	0	2.3	24F..	48	48	0	4.0

[a] See note to Table XIII.

Series 9 shows that brown rock phosphate, dextrose, and a limited supply of calcium carbonate failed to give as good results with cowpeas as raw phosphate alone. For further comparison see Plate LXXVIII.

Thus far it has not seemed necessary to use calcium carbonate alone, because it was thought that the plants would get enough calcium, for full growth from the phosphate, however, in order to avoid criticism at this point calcium carbonate was added to certain pots in the following series. The quantity of this compound was increased to 48 gm. per pot, which is almost five times as much as the application in the preceding series.

By making a comparison of the pots which received raw rock phosphate alone and those which received raw rock and calcium carbonate very little difference in the yield is observed, only 0.6 gm. more in favor of the addition of the lime compound. There is no strong evidence in Table XV to show that the omission of calcium was a mistake. Where lime was applied with rock phosphate and dextrose, the injury by dextrose reported earlier was nullified by the application of lime (Pl. LXXIX and LXXX).

Attention is called to the percentage of phosphorus in the cowpea hay grown in the pots which received soluble phosphorus.

TABLE XV.—*Dry matter produced in cowpeas by Tennessee brown rock phosphate with the addition of dextrose and calcium carbonate—series 10*

Pot No.	Phosphate added.	Dextrose added.	Calcium added.	Hay yield.	Phosphate content.		
					Hay.		Percentage removed from pot.
	Gm.	*Gm.*	*Gm.*	*Gm.*	*Per cent.*	*Mgm.*	
1G...	0	0	10	3.0	0.111	3.37	....
2G...	0	0	10	3.5	....	....	....
3G...	0	0	0	2.8	....	....	....
4G...	0	0	0	3.0	.119	3.57	....
5G...	48	0	0	6.1	....	....	....
6G...	48	0	0	6.3	.246	15.55	0.25
7G...	48	0	0	5.3	....	....	....
8G...	48	0	0	6.8	.236	16.05	.52
9G...	48	0	10	7.4	.156	11.52	.19
10G...	48	0	10	6.2	.239	11.71	.19
11G...	48	48	0	4.9	....	....	....
12G...	48	48	0	4.6	....	....	....
13G...	0	48	48	3.2	.054	1.73	....
14G...	0	48	48	3.3	....	....	....
15G...	48	48	10	6.8	....	....	....
16G...	48	48	10	7.0	.122	8.54	.14
17G...	(a)	0	0	4.9	....	....	....
18G...	(a)	0	0	4.8	.660	31.68	....
19G...	0	0	0	3.0	....	....	....
20G...	0	0	0	3.0	.104	5.19	....
21G...	b 48	0	0	7.0	....	....	....
22G...	48	0	0	6.8	.388	24.06	.39
23G...	48	48	48	6.9	....	....	....
24G...	48	48	48	6.3	.115	7.25	.12

a Soluble phosphate.
b In pots 21 and 22 potassium chlorid was substituted for potassium sulphate.

Under the conditions of this experiment, fermenting dextrose was a failure in bringing about the liberation of phosphorus. Since the use of crop residues is a common farm practice for supplying organic matter, which is said to aid in the liberation of phosphorus, the series next reported was planned with timothy hay and clover substitutes for dextrose.

Timothy and clover cultures on which data are reported in Table III are used for this phase of the problem. Of the duplicate pots the hay from one was taken for analytical study, while the product of the other was ground and returned as organic matter. This series (Table XVI) shows the original treatment with the quantity of air-dried hay turned under. The contents of the pots to which organic matter was added were turned out and the ground material thoroughly incorporated with the sand on December 3, 1914. On January 23, 1915, the pots were planted to the respective crops. They were harvested on April 17, 1915.

The organic matter with phosphate in the above series gave larger returns in most cases than where the phosphate was alone. This increase is probably due to the liberation of phosphorus by the decaying residues or the organic phosphorus in the crop residues themselves.

TABLE XVI.—*Dry matter produced in timothy and red clover by Tennessee brown rock phosphate and crop residues—series 11*

Timothy.				Red clover.			
Pot No.	Phosphate added.	Organic matter added.	Hay yield.	Pot No.	Phosphate added.	Organic matter added.	Hay yield.
	Gm.	*Gm.*	*Gm.*		*Gm.*	*Gm.*	*Gm.*
41[a]	0	0	0.25	71	0	0	0.02
42	0	2.9	.05	72	0	.55	.10
43	11	0	.02	73	11	0	.40
44	11	24.4	.20	74	11	10.5	.10
45	22	0	.30	75	22	0	2.70
46	22	32.7	1.10	76	22	30.5	6.40
47	66	0	3.40	77	66	0	4.70
48	66	61.6	10.70	78	66	57.9	12.50
49	220	0	8.70				
50	220	67.2	11.70				

[a] See series 1, Tables II to VI.

INFLUENCE OF SIZE OF PARTICLES ON THE AVAILABILITY OF PHOSPHORUS IN MINERAL PHOSPHATES

The degree of fineness of rock phosphate particles has been held by many investigators to be an important factor in the availability of mineral phosphates. Dr. Jordan, of the New York Experiment Station, showed rather conclusively that plants supplied with very finely ground rock phosphate contained more phosphorus and produced a greater quantity of dry matter than those supplied with the coarser grades. For the purpose of determining a comparative value of the same rock when ground very fine to that left in particles of a larger size, series 12 (Table XVII) was begun. As a check on the rock which was obtained from the Mount Pleasant mills some lump rock from the same source was secured and ground. These results are reported along with the data on the influence of the size of particles on the availability.

TABLE XVII.—*Relation of size of phosphate particles to the availability of phosphorus by Sixty-Day oats harvested on July 10, 1915—series 12*

Pot No.	Phosphate added.	Fineness.	Grain yield.	Straw yield.	Pot No.	Phosphate added.	Fineness.	Grain yield.	Straw yield.
	Gm.		*Gm.*	*Gm.*		*Gm.*		*Gm.*	*Gm.*
1	0		0	1.20	10	2.6	200 degrees or over	4.00	6.3
2	0		0	1.60	17	2.6	80 to 100 degrees	5.90	6.80
5	2.6	80 to 100 degrees	3.25	6.15	18	2.6	do	7.00	10.05
6	2.6	do	2.05	5.35	19	2.6	100 to 200 degrees	5.80	11.05
7	2.6	100 to 200 degrees	3.70	6.60	20	2.6	do	7.70	11.35
8	2.6	do	4.70	9.30	21	2.6	200 degrees or over	8.65	11.10
9	2.6	200 degrees or over	5.00	8.70	22	2.6	do	7.15	13.20

Pots 5 to 10, inclusive, received the ground rock phosphate as it was obtained from the mills. The degree of fineness varied from that passing a sieve 80 to 100 meshes to the inch to that which would go through a sieve of 200 meshes to the inch. Pots 17 to 22, inclusive, received the ground phosphate which was shipped in the lump form and afterward ground to the same degree of fineness as that ground at the mill.

There is a tendency for the dry matter to increase as the degree of fineness increases. The phosphate received from the mill in lump form was slightly better than that sent to us in a ground condition.

DISCUSSION

Under the conditions of these experiments a fairly large portion of the phosphorus in brown rock phosphate was available for plant growth. The quantity was variable, depending upon the crops and the circumstances attending the full development of the plant. The data show only a very small amount of phosphorus soluble in water and plant food solutions. It is clear that other factors which might bring about availability must be considered. The sand cultures contained very little organic matter; hence, these slight fermentable substances should not be considered. There is nothing left but the plant for our examination and there is abundant proof that the plant itself is a significant item. Since plants excrete large quantities of carbonic acid, there is but little question that this substance plays the primary roll in the liberation of phosphorus.

The reactions with carbon dioxid which occur when tricalcium phosphate is put into sand cultures of the kind described in these pages may be shown in the following manner:

$$\text{(A)}\quad \underbrace{CO_2 + H_2O}_{\text{Gaseous}} \overset{(1)}{\rightleftarrows} \underbrace{H_2CO_3 \overset{(2)}{\rightleftarrows} H^+ + \overline{HCO_3} \overset{(3)}{\rightleftarrows} H^{++} + CO_3}_{\text{In solution}}$$

$$\text{(B)}\quad \underbrace{Ca_3(PO_4)_2}_{\text{Solid}} \overset{(4)}{\rightleftarrows} \underbrace{Ca_3(PO_4)_2 \overset{(5)}{\rightleftarrows} 3Ca^{++} + \overline{\overline{\overline{2PO_4}}}}_{\text{In solution.}}$$

When A and B are mixed, the following equilibria develop:

$$\text{(C)}\quad \overline{\overline{\overline{PO_4}}} + H^+ \overset{(6)}{} \overline{\overline{HPO_4}} \text{ (The ion of reverted phosphate)}$$

$$\overline{\overline{HPO_4}} + H^+ \overset{(7)}{\rightleftarrows} \overline{H_2PO_4} \text{ (The ion of soluble phosphate)}$$

$$\overline{H_2PO_4} + H^+ \overset{(8)}{\rightleftarrows} H_3PO_4$$

Equations A and B make it evident that the hydrogen ion concentration for the various acids will determine the course of the reactions rendering the rock phosphate available. The hydrogen ion concentration is made up of two factors—namely, the concentration and the strength of the acid. Obviously under the conditions of these experiments saturated solutions of rock phosphate and carbonic acid are employed. The relative insolubility of the rock phosphate tends to decrease greatly the concentration of the H^+ from either 6, 7, or 8. The relatively greater solubility of the calcium bicarbonate, since it furnishes $\overline{HCO_3}$, would also tend to decrease the H^+ concentration from carbonic acid, but this factor of common ion effect is of far less importance upon the concentration of the H^+ from H_2CO_3 than the solubility of the tricalcium phosphate upon equations 6, 7, and 8, especially since the Ca^{++} from the $Ca(HCO_3)_2$ is removed by plants.

Assuming equivalent or unit concentrations of the substances H_2CO_3, H_3PO_4, $\overline{H_2PO_4}$, and $\overline{\overline{HPO_4}}$ are present—that is, eliminating the factor of concentration of the substances producing the H—the relative strength of these acids is given by their ionization constants, thus:

$$(1)^a \quad H_2CO_3 \rightleftarrows H^+ + \overline{HCO_3} \qquad Ka^{18^\circ}\ 3.0 \times 10^{-7}$$

$$(6) \quad \overline{\overline{HPO_4}} \rightleftarrows \overline{\overline{\overline{PO_4}}} + H^+ \qquad Ka^{18^\circ}\ 3.6 \times 10^{-13}$$

$$(7) \quad H_2PO_4 \rightleftarrows \overline{\overline{HPO_4}} + H^+ \qquad Ka^{18^\circ}\ 1.95 \times 10^{-7}$$

$$(8) \quad H_3PO_4 \rightleftarrows \overline{H_2PO_4} + H^+ \qquad Ka^{18^\circ}\ 1.1 \times 10^{-2}$$

The mass law for monobasic acids (HAc) has the form $Ka = \frac{(\text{Conc } H^+)\ (\text{Conc Ac})}{\text{Conc HAc}}$. Since the acids of equations 1, 6, and 7 are weak acids ($Ka < 10^{-4}$), the mass law assumes the form $Ka = (\text{Conc } H^+)\ (\text{Conc Ac}) = (\text{Conc } H^+)^2$, because the concentration of HAc is practically unity. The concentrations of H^+ for these equations at 18° C. are for:

$$(1) \quad \sqrt{3 \times 10^{-7}} = 5.5 \times 10^{-4} \text{ for } C^{(1)}H^+$$

$$(6) \quad \sqrt{3.6 \times 10^{-13}} = 6 \times 10^{-7} \text{ for } C^{(6)}H^+$$

$$(7) \quad \sqrt{1.95 \times 10^{-7}} = 4.4 \times 10^{-4} \text{ for } C^{(7)}H^+$$

For the first hydrogen of H_3PO_4 the above expression can not be used, since the amount H_3PO_4 compared to its ions is small rather than large. Here the mass law must be used in its true form, $K = \frac{C\alpha^2}{1 - \alpha}$, where C is equal to the initial concentration of H_3PO_4 and α degrees of ioniza-

[a] See equations, page 508.

tion. For the purpose α is taken equal to 90 per cent, from which the concentration of H is calculated thus:

$$Ka^{18°} = \frac{C\alpha 2}{1-\alpha}, \quad \text{where} \quad (C) = Ka\frac{(1-\alpha)}{\alpha} = \text{concentration of H.}$$

$$\therefore \text{concentration of } H^+(C^{(8)}H^+) = \frac{1.1 \times 10^{-2}(0.1)}{0.9} = \frac{1.1 \times 10^{-3}}{0.9} = 1 \times 10^{-3} = 0.001.$$

It is seen that only the first H of H_3PO_4 can furnish a greater concentration of H^+ than H_2CO_3 for equivalent concentrations. In the actual experiment the concentration of H_3PO_4 is much less than that of H_2CO_3. However, the availability of the rock phosphate by means of H_2CO_3 is not conditioned by the liberation of free H_3PO_4 according to equation 8. Equation 6 or 7 is driven in the direction to remove H^+, would render the tricalcium phosphate more available, but a reaction between ions proceeds if a lesser ionized product be formed. Calculations of the H^+ concentration for equations 1, 6, and 7 shows that for equivalent concentrations the H^+ from carbonic acid is greatly in excess of the H^+ concentration for equations 6 and 7. So if equations 1, 6, and 7 are present simultaneously $\overline{\overline{HPO_4}}$ and $\overline{H_2PO_4}$ of equations 6 and 7 would be formed by the union of H^+ of H_2CO_3 with $\overline{\overline{\overline{PO_4}}}$ and $\overline{\overline{HPO_4}}$, respectively, thus causing more $Ca_3(PO_4)_2$ to dissolve to reestablish the equilibria for equations 6 and 7. It is a fact, however, that a greater concentration of H_2CO_3 is present than any of the ionizing substances, as $\overline{\overline{HPO_4}}$, $\overline{H_2PO_4}$, or H_3PO_4. This would increase the rate of availability of the tricalcium phosphate.

These calculations are borne out by the fact that more $Ca_3(PO_4)_2$ dissolved in water containing H_2CO_3 than in pure water. Seidel's solubility tables state that 1 liter of water saturated with H_2CO_3 dissolves 0.15 to 0.30 gm. of $Ca_3(PO_4)_2$ at 25°, while 1 liter of pure water dissolved only 0.01 to 0.10 gm. of $Ca_3(PO_4)_2$ at 25°.

Reactions 6 and 7 may be shown in the nonionic form as follows:

$$Ca_3(PO_4)_2 + 2H_2CO_3 \leftrightarrows Ca_2H_2(PO_4)_2 + CaH_2(CO_3)_2 \text{ or}$$
$$Ca_3(PO_4)_2 + 2H_2CO_3 \leftrightarrows Ca_2(HPO_4)_2 + Ca(HCO_3)_2$$
$$Ca_2H_2(PO_4)_2 + 2H_2CO_3 \rightleftarrows \underset{\substack{\downarrow \\ \text{or} \\ Ca(H_2PO_4)_2}}{CaH_4(PO_4)_2} + \underset{\substack{\downarrow \\ \text{or} \\ Ca(HCO_3)_2}}{CaH_2(CO_3)_2}$$

In the first equation calcium is found in a form readily assimilated by plants, and in the second the monocalcium phosphate is in a very assimilable form. On this equation we have based our belief that there is no necessity for applying lime to sand cultures to which had previously been

added raw rock phosphate. When the calcium bicarbonate and monocalcium phosphate are both removed from the medium of growth by plants, the reaction is driven rapidly to the right. Mass relationship in a mixture of this kind confirms such an interpretation as the one presented above. Our first assumption, that plants should get their calcium from rock phosphate in the same manner that they get their phosphorus, is supported at several points in this work. This must be so, since the calcium is furnished by the calcium salt of phosphoric acid or by the bicarbonate. There was no greater growth when calcium carbonate was added than where raw rock alone was used. In fact, the growth might be even less, since calcium carbonate might furnish a greater concentration of $Ca(HCO_3)_2$ or HCO_3, which might decrease the concentration of H from equation 1, thus decreasing the rate of the availability of rock phosphate.

The most marked feature of the investigation is the difference of the availability of the various minerals. The fact that the crop yields increase as the application of the brown rock phosphate was increased indicates that a portion of the phosphorus was readily assimilated while the plants were young, and that by the time these plants became well established they were able to utilize the more insoluble form. If we are to assume that a part of the phosphorus is of animal origin, this position probably is more tenable, or on the other hand, through long years of weathering the compound had been so changed that a portion was more easily taken up by plants than before weathering began.

There is an indication that the crops grown first took up the more available phosphorus and that the second crop made very slow growth because the more soluble phosphorus was removed by the first crop and nothing left but the rather insoluble for later crops. These points have proof from the cowpeas on the large application series and the clover on the crop residue series.

Brown rock phosphate and Florida soft rock phosphate lead the others in supplying available phosphorus for plant nutrition, especially for clover. The brown rock phosphate leads for all the crops. These two phosphates gave the largest quantity of phosphorus soluble in water and plant-food solutions. The results indicate a relation in solubility in plant-food solution and the availability for plants.

The difference in the assimilation of these phosphates can not be attributed to the degree of fineness of the particles, since they were all ground, so that the entire sample passed through a sieve of 100 meshes to the inch. If the degree of fineness influenced the results, the differences then come from the size of particles, which were smaller than those found in commercial phosphates.

The variation in the agricultural value of the six mineral phosphates studied is difficult to explain. Their productive powers seemed not to

have any direct relation to the amount of phosphorus which they contained. Brown rock, which had the smallest amount of phosphorus, produced the most satisfactory yields. The differences must be attributed to modes of formation and weathering since the minerals were laid down.

SUMMARY

(1) Phosphorus in rock phosphate can be assimilated by farm crops in sand cultures under greenhouse conditions, even in the absence of decaying residues.

(2) Crop residues, when employed in conjunction with brown rock phosphates, were beneficial.

(3) Tennessee brown rock phosphate, Florida soft rock phosphate, and Tennessee blue rock phosphate in the heavier applications proved superior to South Carolina land rock phosphate, Utah rock phosphate, and Canadian apatite, for oats, clover, and cowpeas when grown in sand.

(4) The phosphorus in brown rock phosphate and Florida soft rock phosphate was more soluble in water and in plant-food solutions than the phosphorus in other mineral phosphates. The superiority of these two phosphates over the others tested is shown chiefly by the first crop.

(5) Chemical analysis showed that the plant-food solutions applied did not appreciably modify the results.

(6) The cereals produced as satisfactory yields as the legumes.

(7) The crop yields tended to increase as the application of rock phosphate increased up to a point where the size of the pots seemed to be a limiting factor, apatite being the only exception.

(8) The plants obtained their calcium, as well as their phosphorus, from brown rock phosphates. No better results were secured when calcium carbonate was applied than when rock phosphate alone was used.

(9) There was no particular relation between the citric-acid-soluble phosphorus and the availability of these phosphates for plants.

(10) Dextrose, when used as a fermentable substance, was harmful.

(11) The degree of fineness is a factor which determines to some extent the availability of rock phosphate, as indicated by the brown rock.

(12) These investigations extended over a period of 3½ years, and embrace results from 700 pot cultures and 400 phosphorus determinations.

LITERATURE CITED

(1) BISHOP, W. H.
1894. Report of pot experiments with phosphates. Del. Agr. Exp. Sta. 6th Ann. Rpt., 1893, p. 193-202, illus.

(2) BROOKS, W. P.
1898. Natural phosphates compared with each other and with acid phosphate. *In* Mass. Hatch Agr. Exp. Sta. 10th Ann. Rpt., [1896/97], p. 14-19.
Reviews work done by Goessmann.

(3) ———.
1901. The relative value of different phosphates. *In* Mass. Hatch Agr. Exp. Sta. 13th Ann. Rpt., [1899/1900], p. 101-105.

(4) DYER, B.
1884. Comparison of dissolved and undissolved phosphates. (Abstract.) *In* Jour. Chem. Soc. [London], v. 46, Abstracts, p. 774. 1884. Original article in Jour. Roy. Agr. Soc. England, s. 2, v. 20, p. 113-126. 1884. Not seen.

(5) FREAR, William.
1887. Agricultural experiment work for 1885 and 1886. II. Experiments with different kinds of phosphoric acid. Penn. State, Col. Rpt., 1886, p. 124-131.

(6) HARTWELL, B. L., and PEMBER, F. R.
1912. The effect of cow dung on the availability of rock phosphate. R. I. Agr. Exp. Sta. Bul. 151, p. 165-174, 1 pl.

(7) HESS, E. H.
1896. Experiments with soluble, reverted and insoluble phosphoric acid. Penn. Agr. Exp. Sta. Ann. Rpt., 1895, p. 157-210.

(8) HOPKINS, C. G., MOSIER, J. G., PETTIT, J. H., and FISHER, O. S.
1913. McDonough county soils. Ill. Agr. Exp. Sta. Soil Rpt. 7, 46 p., 7 fig., 2 col. maps.

(9) JOHNSON, S. W.
1890. Field experiments in 1889. *In* Conn. Agr. Exp. Sta. Ann. Rpt. 1889, p. 203-232.

(10) JORDAN, W. H.
1895. Field experiments with fertilizers. *In* Maine Agr. Exp. Sta. Rpt., 1894, p. 16-32.

(11) ———.
1913. Studies in plant nutrition. I. N. Y. Agr. Exp. Sta. Bul. 358, 30 p.

(12) KRÖBER, E.
1909. Über das Löslichwerden der Phosphorsäure aus wasserunlöslichen Verbindungen unter der Einwirkung von Bakterien und Hefen. *In* Jour. Landw., Bd. 57, Heft 1, p. 5-80.

(13) LUPTON, N. T.
1893. The effect of decomposing organic matter on natural phosphates. Ala. Agr. Exp. Sta. Bul. 48, 80 p.

(14) McDOWELL, M. S.
1908. Is the phosphoric acid of floats made soluble by rotting manure? Penn. Agr. Exp. Sta. Ann. Rpt., 1907/08, p. 175-178.

(15) MERRILL, L. H.
1899. Box experiments with phosphoric acid from different sources. Maine Agr. Exp. Sta. 14th Ann. Rpt., 1898, p. 64-74, 7 pl.

(16) NEWMAN, J. S.
1889. Cotton—experiments with fertilizers. *In* Ala. Agr. Exp. Sta. Bul. 5, n. s., p. 3-13.

(17) NEWMAN, J. S., and CLAYTON, James.
1891. Experiments with cotton—1890. Ala. Agr. Exp. Sta. Bul. 22, n. s., 29 p.

(18) PATTERSON, H. J.
1907. Fertilizer experiments with different sources of phosphoric acid. Md. Agr. Exp. Sta. Bul. 114, p. 113–144.

(19) PFEIFFER, Th., and THURMAN, H.
1896. Über das Verhalten einiger Phosphate bei der Kompostierung. *In* Landw. Vers. Stat., Bd. 47, Heft 4/5, p. 343–356.

(20) PRIANICHNIKOW, D. N.
1899. Étude sur la valeur relative des phosphates minéraux. *In* Ann. Agron., t. 25, no. 4, p. 177–187.

(21) RUSSELL, H. L.
1913. Report of the director. Availability of phosphate to various crops. Wis. Agr. Exp. Sta. Bul. 240, p. 22–23, fig. 11.

(22) SCHLOESSING, T., jr.
1902. A study of the phosphorus nutrition of plants. (Abstract.) *In* Exp. Sta. Rec., v. 14, no. 3, p. 233. 1902. Original article in Compt. Rend. Acad. Sci. [Paris], t. 134, no. 1, p. 53–55. 1902. Not seen.

(23) SCHUTT, F. T.
1897. Report of the chemist. The fermenting of manure with finely ground mineral phosphate. *In* Canada Exp. Farms Rpts., 1896, p. 196.

(24) [THORNE, C. E.]
1910. Plans and summary tables of the experiments at the central farm, Wooster, on the maintenance of soil fertility. Ohio Agr. Exp. Sta. Circ. 104, 20 p.

(25) ———
1913. Farm manures. 242 p., illus. New York, London.

(26) TOTTINGHAM, W., E., HOFFMAN, C.
1913. Nature of the changes in the solubility and availability of phosphorus in fermenting mixtures. Wis. Agr. Exp. Sta. Research Bul. 29, p. 273–321, 3 fig.

(27) TRUOG, E.
1912. Factors influencing the availability of rock phosphate. Wis. Agr. Exp. Sta. Research Bul. 20, p. 17–51, 6 fig.

(28) Verband landwirtschaftlicher Versuchs-Stationen im Deutschen Reiche.
1907. Vorläufige Mitteilung der Beschlüsse der XXIV. Hauptversammlung des Verbandes zu Dresden am 14. September 1907. *In* Landw. Vers. Stat., Bd. 67, Heft 5/6, p. 321–329.

(29) VOELCKER, A.
1880. Comparative value of soluble and insoluble phosphates. (Abstract.) *In* Jour. Chem. Soc. [London], v. 40, Abstracts, p. 640–641. 1881. Original article in Jour. Roy. Soc. Agr. Soc. England, s. 2, v. 16, p. 152–159. 1880. Not seen.

(30) WHEELER, H. J., and ADAMS, G. E.
1900. The needs and treatment of the Warwick Plain and other sandy soils of Rhode Island. R. I. Agr. Exp. Sta. Bul. 68, p. 159–174.

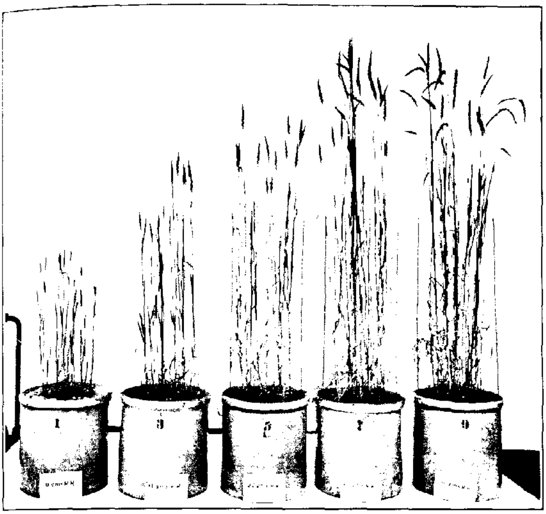
(31) ——— ———
1906. A comparison of nine different phosphates upon limed and unlimed land with several varieties of plants. R. I. Agr. Exp. Sta. Bul. 114, p. 117–137.

(32) ——— ———
1907. Continued test of nine different phosphates upon limed and unlimed land with several varieties of plants. R. I. Agr. Exp. Sta. Bul. 118, p. 55–86.

PLATE LXXIII

Effect of varying quantities of Tennessee brown rock phosphates on plant growth:

Fig. 1.—Spring wheat. (Table II, Series 1A.)
Fig. 2.—Sixty-Day oats. (Table II, series 1B.)



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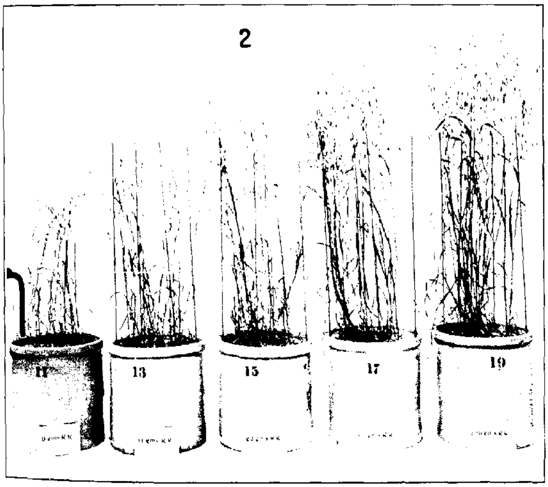
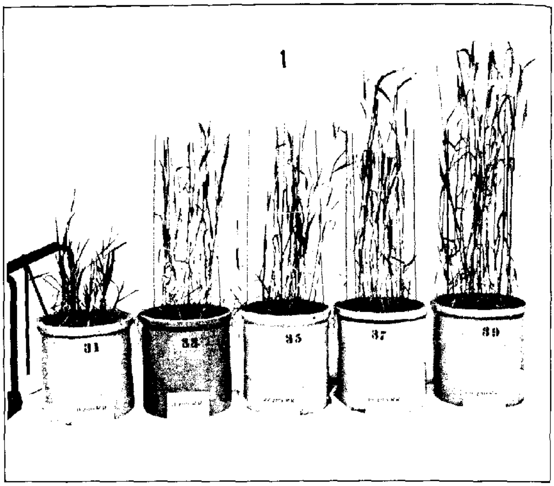




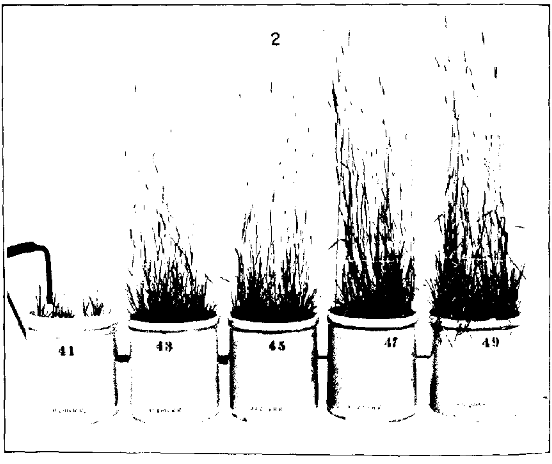


PLATE LXXIV

Effect of varying quantities of Tennessee brown rock phosphate on plant growth:

Fig. 1.—Barley. (Table VI.)

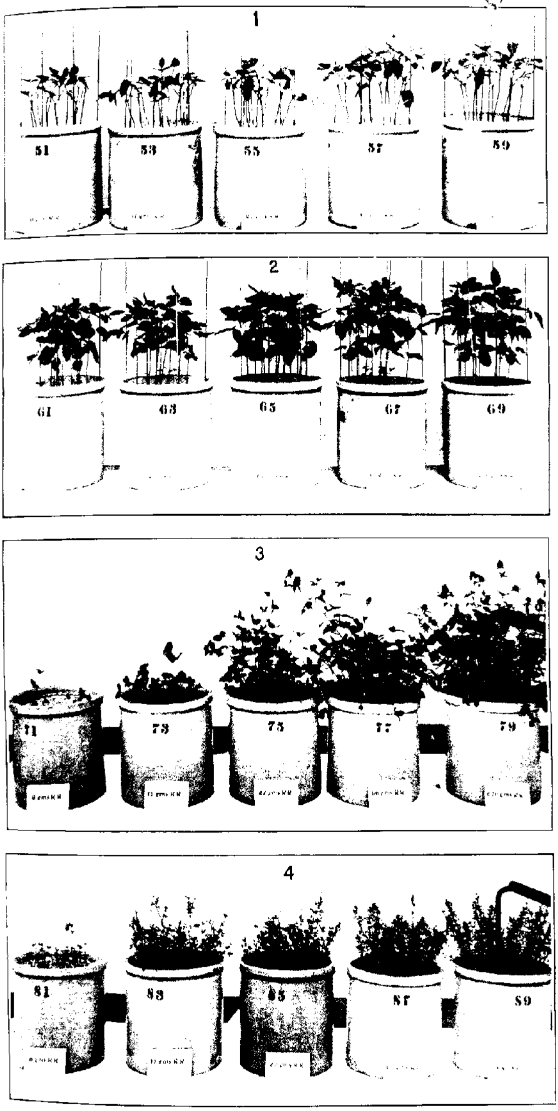
Fig. 2.—Timothy. (Table III, series 1E.)

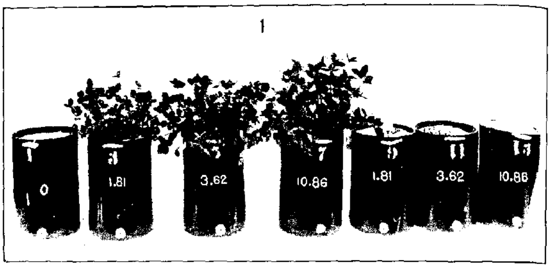
37770°—16——4

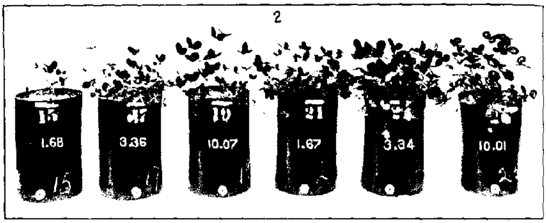
PLATE LXXV

Effect of varying quantities of Tennessee brown rock phosphate on plant growth:

Fig. 1.—Cowpeas. (Table IV, series 1F.)
Fig. 2.—Soybeans. (Table IV, series 1G.) Photographed just before cutting.
Fig. 3.—Red clover. (Table III, series 1H.)
Fig. 4.—Alfalfa. (Table V.) Photographed before first cutting.


1
51
53
55
57
59
2
61
63
65
67
69
3
71
73
75
77
79
4
81
83
85
87
89


1
1
0
3
1.81
5
3.62
7
10.86
9
1.81
11
3.62
13
10.86


2
15
1.68
3.36
10.07
21
1.67
3.34
10.01

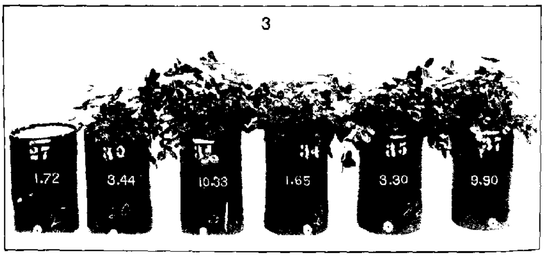
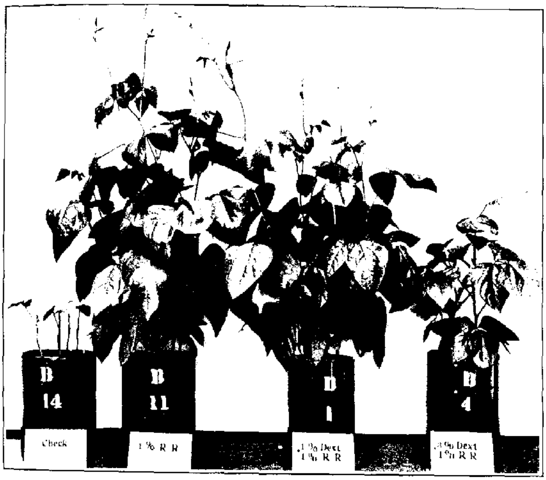

3
27
1.72
30
3.44
10.33
34
1.65
35
3.30
9.90

PLATE LXXVI

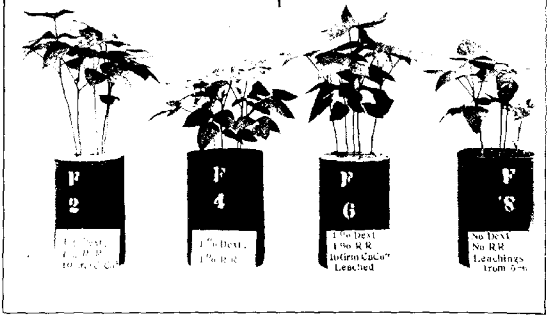
Effect of different kinds of mineral phosphate applied in different quantities for red clover. (Table VII.) Photograped just before first cutting.

PLATE LXXVII

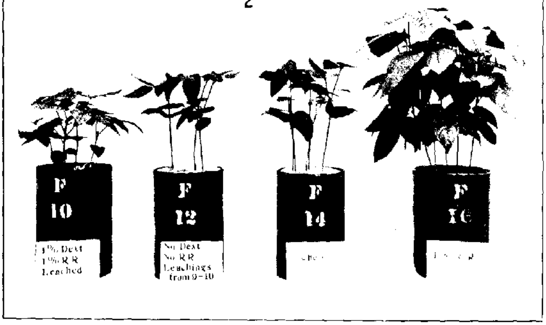
Cowpeas, showing the comparative effect of Tennessee brown rock phosphate alone and in combination with dextrose. (Table XII.)


B
14
Check
B
11
1% R R
B
1
.1% Dext
1% R R
B
4
.3% Dext
1% R R

1


F 2
F 4
1% Dext.
1% R R
F 6
1% Dext
1% R R
10 Grm CaCO3
Leached
F 8
No Dext
No R R
Leachings
from 5-6

2


F 10
1% Dext
1% R R
Leached
F 12
No Dext
No R R
Leachings
from 9-10
F 14
F 16

3

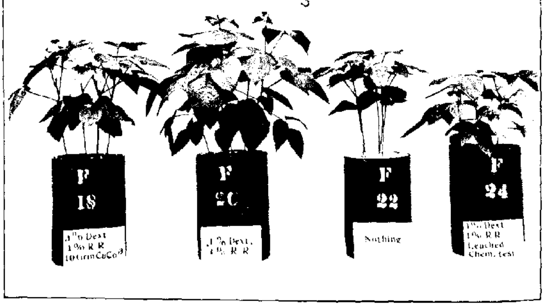

F 18
1% Dext
1% R R
10 Grm CaCO3
F 20
1% Dext.
1% R R
F 22
Nothing
F 24
1% Dext
1% R R
Leached
Chem. test

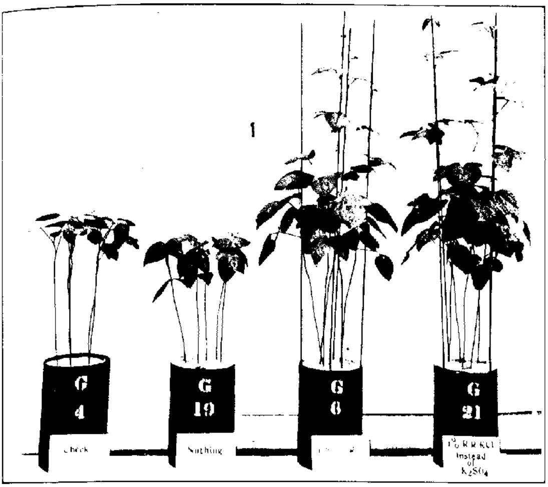
PLATE LXXVIII

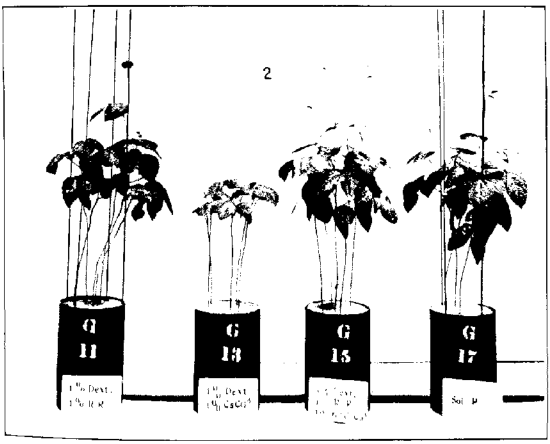
Cowpeas, showing the comparison of their growth when treated with Tennessee brown rock phosphate, phosphate and dextrose, and phosphate, dextrose, and calcium carbonate. (Table XIV.) Photographed just before harvesting.

PLATE LXXIX

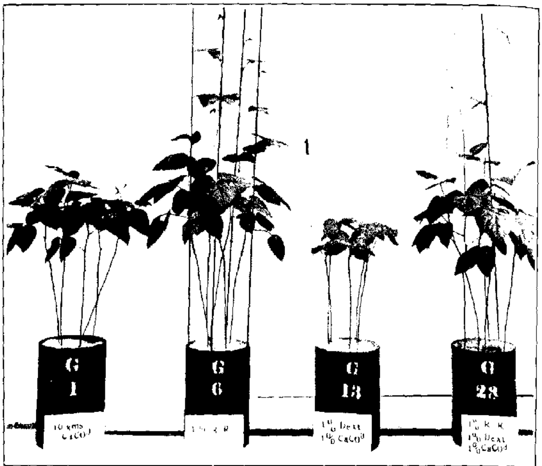
Effect of different substances on the growth of cowpeas:

Fig. 1.—Growth after the addition of varying quantities of raw rock. (Table XV.)
Fig. 2.—Growth after the addition of dextrose and soluble phosphate. (Table XV.)


1
G
4
Check
G
19
Nothing
G
6
G
21
Instead
of
K_2SO_4


2
G
11
G
13
G
15
G
17

1



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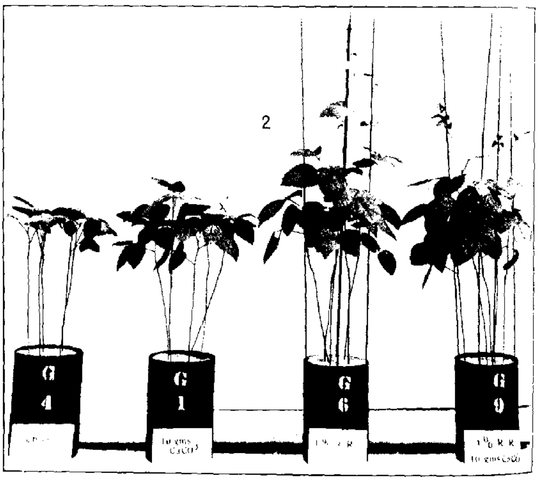

PLATE LXXX

Effect of various substances and combinations on the growth of cowpeas:

Fig. 1.—Effect of adding lime, phosphate rock, dextrose and lime, and phosphate rock, dextrose, and lime to the soil. (Table XV.)

Fig. 2.—Effect of adding nothing, lime, phosphate rock, and phosphate rock and lime to the soil. (Table XV.)